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THE EFFECTS OF HELICOPTER VIBRATION ON THE SPINAL SYSTEM

FINAL REPORT

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The UH-1H specific seating environment was studied in both static and vibration modes to assess its contribution to the production of backache in pilots. Subjective measures of pain and objective measures of lumbar muscle fatigue were used to determine a subject's response to a 2-hour exposure to the UH-1H seated posture. Another outcome measure was the change in the characteristic motion of the back surface as a result of exposure to 2 hours of typical UH-1H vertical vibration. Subjects were also tested for their mechanical response to each of three axes of vibration. Major findings included: 1) a marginally significant level of lumbar muscle fatigue due to a statically held posture in men; 2) in men there was a marginal significantly greater lumbar musculature fatigue due to a sustained static posture than that found due to sitting and vibrating up and down; 3) all subjects (male and female) indicated significant increase in pain due to sustained sitting in either a static or vibrating UH-1H cockpit environment; 4) the males exhibited significantly greater pain due to a sustained static seated posture than due to the same posture held while being vibrated either side to

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side or up and down; and 5) there were significant changes in the way the surface of the back moved during up and down vibration as a result of exposure to the UH-1H, vertically vibrated seated posture. Keywords: Helicopter pilot seats, Flight crew posture;

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SUMMARY

1. A subject pool (males and females) with no previous experience of low back pain was identified and used in this study.
2. Exposure to a static seated posture caused significant changes in the subjectively and objectively assessed responses to fatigue.
3. Exposure to a vibrated, seated posture caused significant changes in the subjectively assessed fatigue. It also caused changes (non-significant) in objectively assessed fatigue.
4. A photogrammetric technique was used to assess motion of the back surface during and as a function of exposure to vibration.
5. Motion characteristics of discrete points located on the surface of the back changed in response to exposure to sustained vertical vibration.
6. The transmissibility of the seated operator was assessed and modeled.
7. Correlations between objective and subjective factors were poor.

FOREWARD

For the protection of human subjects the investigator(s) have adhered to policies of applicable Federal Law 45CFR46.

Citation of commercial organizations and trade names in this report does not constitute an official Department of the Army endorsement or approval of the products or services of these organizations.

ACKNOWLEDGMENT

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INTRODUCTION

Severe, acute and sometimes debilitating backaches have been reported by pilots of two-bladed helicopters. U.S. Army operational needs include minimizing low back pain production in UH-1H helicopter pilots (Shanahan and Reading, 1984). Vibration may be a major contributor to the problem, but a lack of information on muscular tolerance to vibration and the role of vibration in fatigue makes a solution through appropriate equipment design exceedingly difficult. Chronic back ailments in aircrewmen having several thousand hours of flight experience deplete the aviation manpower resource and reduce its effectiveness. The cause of the ailments is thought to be vibration-induced damage to the spine. Data on joint morphology resulting from long-term exposure to vibration do not exist, but are essential for establishing standards to limit the hazard. Crewmen integration into sophisticated or closed-loop fire control systems has been proposed in the Advanced Combat Vehicle Technology program and the Advanced Attack Helicopter program. Vibration plays a significant role in the effectiveness of man in such systems, yet there is insufficient information to account adequately for human response in the design of such systems. Vibration is known to adversely affect health. However, standards do not exist which relate vibration exposure in the military-unique environment to these known hazards.

To assess these effects in the Army rotary wing aviator, the investigators planned to gather biomechanical data to assess these hypotheses:

(1) The biomechanical effects of helicopter vibration will be significantly modified by the posture of the aviator and, thus, the layout of the controls, the cockpit, and the seat design.

(2) The effects of these vibrations will be sufficient to cause soft and hard tissue stress and subsequent injury.

The investigators felt that they could make a unique contribution toward this goal due to their history of assessing the biomechanics of vibration environments and various conditions of low back pain. The point of the work for the Army was to provide objective correlates for the assessment of the effect of vibration and seating on pain production in the pilot. The volunteer population available consisted of people who had no history of low back pain or flight in UH-1H helicopters. Thus, there was an opportunity to assess the onset and duration of pain during the simulated vibration/flight environment in these unaffected, healthy normal subjects.

The second year of work (on contract: University of Vermont Extramural Contract No. USDAMD 17-84-C-4140) dealt with using methodologies and equipment in concert with recommendations from USAARL. The past year's work specifically addressed the basis for the techniques used in this work (Pope et al., 1983).

4. MATERIALS AND METHODS

4.1 Fatigue Assessment Using 1) Center Frequency of Erector Spinae EMG Spectrum and 2) Visual Analog Discomfort Scale

In order to perform an objective assessment of muscle fatigue in a UH-1H cockpit seating environment (Figure 1), instrumentation was

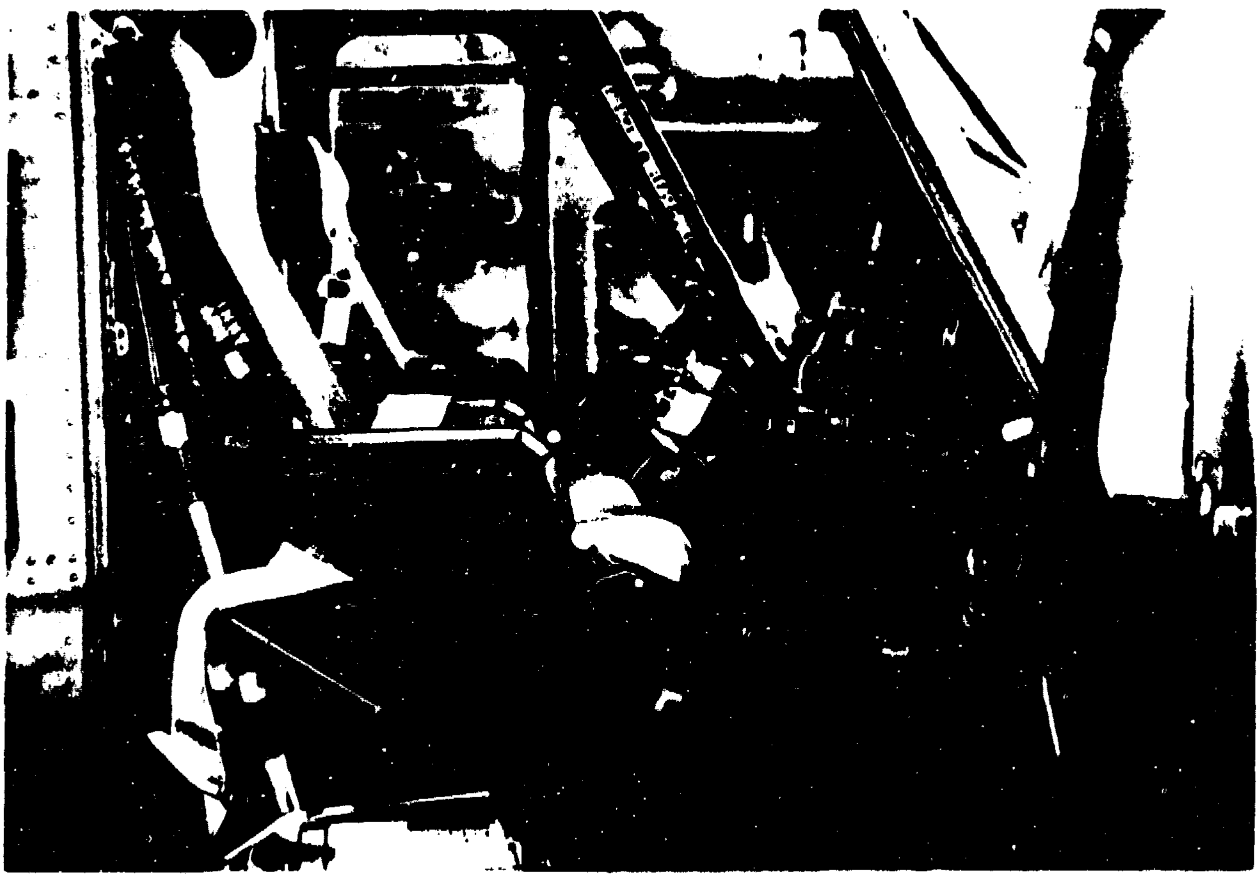


Figure 1. Side view of UH-1H cockpit seating environment.

developed to sense and use as an outcome measure the shift in the center frequency of the EMG spectrum of the erector spinae musculature. Subjective assessment of fatigue was accomplished by means of a visual analog scale indicating pain as a function of duration of exposure to the seated environment. Twenty subjects (10 male and 10 female) (Tables I, II, III) were exposed to the same seating environment (in terms of both static posture and vibration exposure) as that experienced by the UH-1H helicopter pilot. The vibration environment of a UH-1H helicopter was recorded and reproduced using a servohydraulic vibration simulator. Each exposure lasted two hours.

The human spine is a complex mechanical structure which performs the dual task of motion production and load bearing. Since the bony spine is supported and moved by its surrounding muscular and ligamentous tissue, changes in their mechanical capacities could adversely affect the function of this system. Of great interest, then, is the response of the tissues to mechanically damaging environments. It is known from the work of Weisman, Pope and Johnson (1980) that repeated loading of ligaments in the knee makes the ligament mechanically softer (less stiff) and decreases its ultimate strength. It is difficult to measure changes of mechanical strength in lumbar ligamentous elements directly. Therefore, the capacity to monitor behavior or strength changes in muscle would be very useful.

The present study was undertaken to develop methods for describing, objectively and subjectively, fatigue in the lower back and buttocks of subjects in a UH-1H flight environment. To assess the effects of vibration in the Army rotary wing aviator,

TABLE I.

Static test subjects

	Inits	Age	Ht(cm)	Wt(N)	Ht(in)	Wt(lbf)
Males	IS	32	177.8	734.3	70	165
	SR	23	172.7	734.3	68	165
	SA	23	167.6	600.8	66	135
	MH	22	172.7	712.0	68	160
	DL	27	180.3	778.8	71	175
	CH	28	172.7	712.0	68	160
	BW	23	177.8	734.3	70	165
	ST	33	188.0	734.3	74	165
	CB	27	180.3	712.0	71	160
	BB	29	182.9	823.3	72	185
	n	10	10	10	10	10
	mean	26.7	177.3	727.6	69.8	163.5
	sd	3.9	6.0	56.5	2.3	12.7
Females	RC	29	167.6	534.0	66	120
	ES	29	165.1	511.8	65	115
	LC	30	160.0	578.5	63	130
	LW	26	162.6	600.8	64	135
	JK	34	165.1	623.0	65	140
	JG	22	160.0	600.8	63	135
	RC	25	172.7	623.0	68	140
	EP	22	177.8	623.0	70	140
	SU	26	180.3	645.3	71	145
	LF	36	160.0	556.3	63	125
	n	10	10	10	10	10
	mean	27.9	167.1	589.6	65.8	132.5
	sd	4.7	7.5	43.6	2.9	9.8

TABLE II.

Fore-Aft vibration test subjects

	Inits	Age	Ht(cm)	Wt(N)	Ht(in)	Wt(lbf)
Males	SA	23	165.1	600.8	65	135
	CH	28	172.7	712.0	68	160
	SR	23	172.7	734.3	68	165
	ST	33	188.0	734.3	74	165
	DL	27	180.3	778.8	71	175
	IS	32	177.8	734.3	70	165
	MH	22	172.7	712.0	68	160
	CB	27	180.3	712.0	71	160
	BW	23	177.8	734.3	70	165
	BB	29	182.9	823.3	72	185
	n	10	10	10	10	10
	mean	26.7	177.0	727.6	69.7	163.5
	sd	3.9	6.5	56.5	2.5	12.7
Females	LF	36	160.0	556.3	63	125
	JK	34	165.1	623.0	65	140
	ES	29	165.1	511.8	65	115
	LW	26	162.6	600.8	64	135
	RC	29	165.1	534.0	65	120
	JG	22	160.0	600.8	63	135
	RC	25	172.7	623.0	68	140
	EP	22	177.8	623.0	70	140
	LB	30	160.0	578.5	63	130
	MM	23	177.8	734.3	70	165
	n	10	10	10	10	10
	mean	27.6	166.6	598.5	65.6	134.5
	sd	4.9	7.0	61.6	2.8	13.8

TABLE III.

Side-side vibration and up-down vibration test subjects

	Inits	Age	Ht(cm)	Wt(N)	Ht(in)	Wt(lbf)
Males	SA	24	167.6	614.1	66	138
	SR	23	172.7	734.3	68	165
	ST	33	188.0	734.3	74	165
	CH	28	172.7	712.0	68	160
	JW	26	167.6	667.5	66	150
	IS	32	177.8	734.3	70	165
	DL	27	180.3	778.8	71	175
	CB	27	180.3	712.0	71	160
	BB	29	182.9	823.3	72	185
	MH	22	172.7	712.0	68	160
	n	10	10	10	10	10
	mean	27.1	176.3	722.2	69.4	162.3
	sd	3.6	6.7	56.6	2.6	12.7
Females	LW	26	162.6	600.8	64	135
	JG	22	160.0	600.8	63	135
	EP	22	177.8	623.0	70	140
	LB	30	160.0	578.5	63	130
	JC	21	167.6	645.3	66	145
	LF	36	160.0	556.3	63	125
	ES	29	165.1	534.0	65	120
	MM	23	177.8	734.3	70	165
	RC	25	172.7	623.0	68	140
	RC	29	165.1	534.0	65	120
	n	10	10	10	10	10
	mean	26.3	166.9	603.0	65.7	135.5
	sd	4.7	7.0	59.7	2.8	13.4

biomechanical data were gathered in order to address the following hypotheses:

(1) There is no biomechanical effect of helicopter vibration, because of its (the vibration's) significant modification due to the posture of the aviator, as well as the layout of the controls, the cockpit, and the seat design.

(2) The effects of these vibrations would not be sufficient to cause soft and hard tissue stress and subsequent injury.

Two test methods were used for these evaluations: (1) the decrease of the center frequency of the power spectrum of the lumbar musculature's electromyographic (EMG) signal and (2) the operators' subjective assessment of their pain in the lower back and buttocks by means of a visual analog scale (VAS).

Shanahan and Reading (1984) have suggested that the problem of low back pain and pain reported by helicopter pilots stems from the necessity for pilots to assume slumped and asymmetric postures for extended periods of time with little chance to change their positions significantly. They have also suggested that this probably leads to spasm of paraspinal musculature and increased sensitivity of the buttocks.

In order to determine whether muscle electrical activity changes could indicate fatigue of the muscles, it was necessary to perform an initial study on a group of subjects who had no history of back pain. The experiments performed sought to find a change in the muscle response due to the sustained posture and vibration environment. Because a characteristic of muscle contraction is the production of a

complex electrical signal arising from the summation of asynchronously firing muscle motor units, the muscle electrical activity or EMG signal can be monitored using surface or wire electrodes. In order to evaluate the complex EMG signal, a technique called spectral analysis was used to decompose the signal into its simpler components. Hence it was possible to measure muscle electrical activity changes in a group of people exposed to this environment.

The subjects' lumbar electromyographic signals were detected by means of bipolar surface electrode pairs (with a center to center distance of 2.5 cm) placed at the L3 level approximately 3 cm lateral to the midline of the back. The silver-silver chloride electrodes were 12.5 mm in diameter (In Vivo Metric Systems) and were filled with a conductive gel that provided an interface with the skin. The application site was lightly sanded and prepared with a skin conditioner ("Skin Cleaner," In Vivo Metric Systems item #E403) to maximize adhesion and electrical conductivity. Because of variable torso sizes, it was felt that the protocol of Andersson, Jonsson and Ortengren (1974), that of placing the electrodes a set distance from midline, was inappropriate. A modified technique, that of placing electrodes on the belly of the erector spinae muscle determined by palpation, ensured a placement for maximum EMG signal amplitude. Interelectrode resistances were measured and ensured to be less than 5,000 ohms. EMG signals were amplified using instrumentation developed in year one of the contract (Pope et al., 1983) to process the surface electromyographic (EMG) activity of the spinal musculature. The EMG amplifiers used delivered a clean output with a high signal-to-noise ratio. The specifications of the amplifiers were

as follows: signal-to-noise ratio of 30:1, an input impedance of 2 megohms, low pass filtering at 10 KHz with a 60 Hz rejection, and a frequency response from DC - 70 KHz. Four channels of data were recorded (Figure 2) on a TEAC FM data recorder: left and right erector spinae EMG activity, RMS value of right EMG, and force as indicated by a load cell attached to a chest harness. For further description of the previous work and instrumentation in this set-up, see the previous year's report (Pope et al., 1983).

Since a correlation had been found between muscle force production and EMG activity (Andersson, Ortengren and Schultz, 1980), the next step was to evaluate the fatigue of the muscle via spectral analysis of the EMG signal. Previous workers (Lindstrom, Kadefors and Petersen, 1977; Lindstrom, Magnusson and Petersen, 1970; Lloyd, 1971; Petrofsky, 1980; Petrofsky, Dahms and Lind, 1975; Viitasalo and Komi, 1977) have shown that there is a change in muscle firing frequency before and after exertion. A spectrum analyzer was used to determine the shift of the center frequency of the EMG power spectrum.

In order to prove EMG center frequency shift as a tool to assess muscle fatigue, twenty subjects (10 males, 10 females) (Table IV) were evaluated for their force versus EMG activity. Each subject was tested on each day over a six-day period. The first day of testing was a day of training for the subject to become acclimated to the test. Generally, the testing on each day consisted of monitoring the subject's EMG activity and force production during a maximum or percentage of maximum voluntary contraction (MVC). Subjects were seated (Figure 3) in a UH-1H seat while wearing a seat belt and

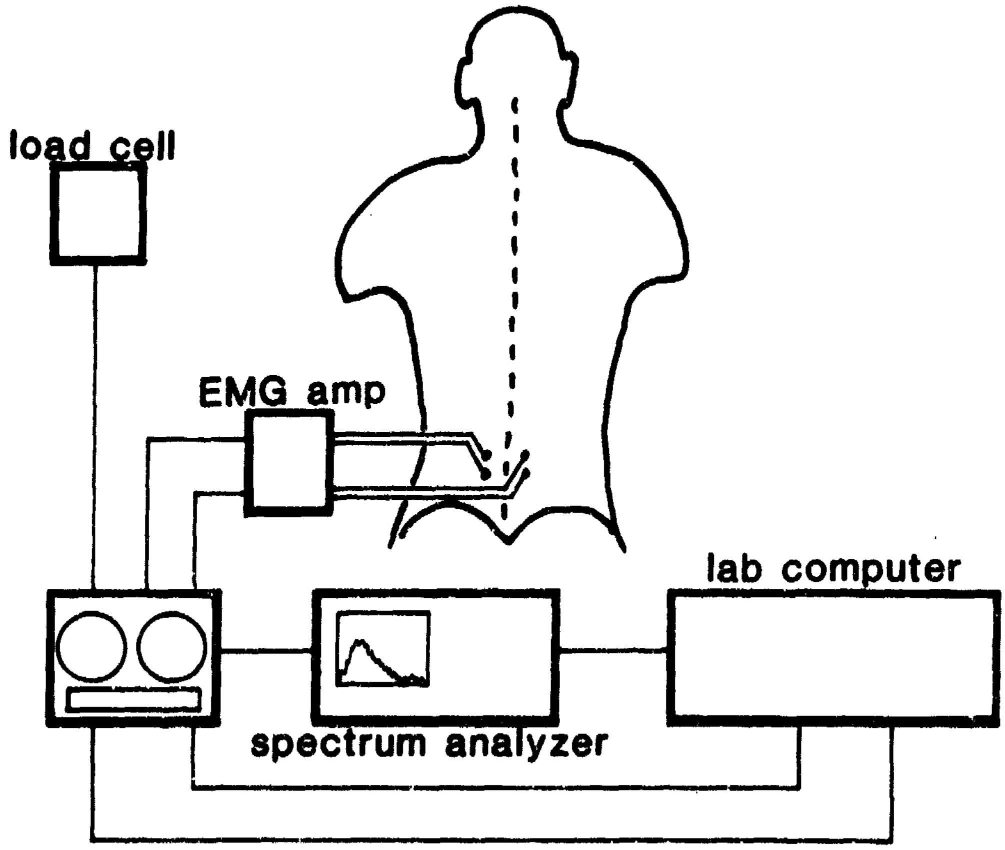


Figure 2. Schematic of the instrumentation set-up used to monitor the center frequency shift of the erector spinae muscle electromyographic activity spectrum due to isometric extension efforts held to exhaustion (fatigue).

TABLE IV.

Anthropometric data of 20 subjects used in the EMG vs. force, muscle fatigue and static seating tests

		Males	Females
Age (years)	mean	27.7	27.0
	S.D.	5.6	5.3
Height (cm)	mean	177.3	164.2
	S.D.	6.1	5.7
Weight (kg)	mean	74.1	57.4
	S.D.	7.0	5.5
Weight (N)	mean	730.7	566.0
	S.D.	69.0	54.2

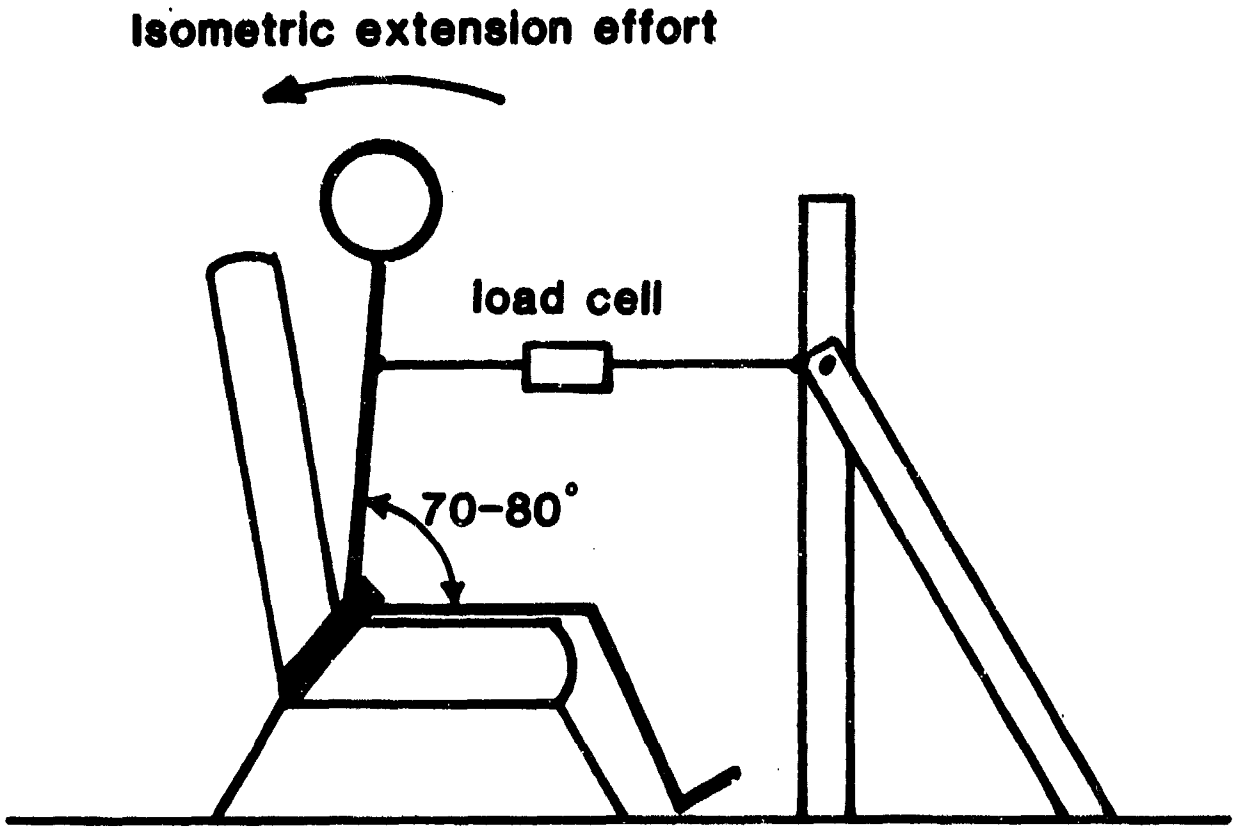
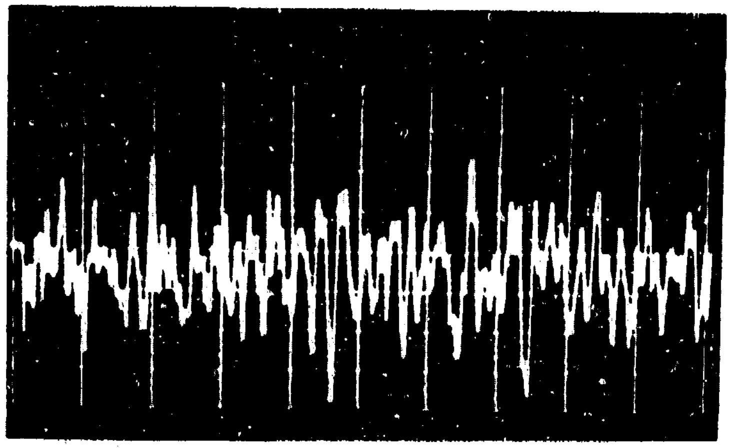


Figure 3. Side view of set-up used to evaluate fatiguing isometric extension efforts on the lumbar musculature.

maintaining a femur-to-back angle of 70-80°. A chest harness was worn which transmitted horizontal forces from the torso to a vertical support. The force exerted was monitored by a load cell and displayed on a digital read-out so that the subject could see his force level and maintain a steady contraction. Prior to each day's fatigue test, three MVC efforts were performed in order to select the maximum as the 100% MVC. Subjects also held, for a few seconds, various percentages of their MVC (80, 60, 45, 37.5, 30).

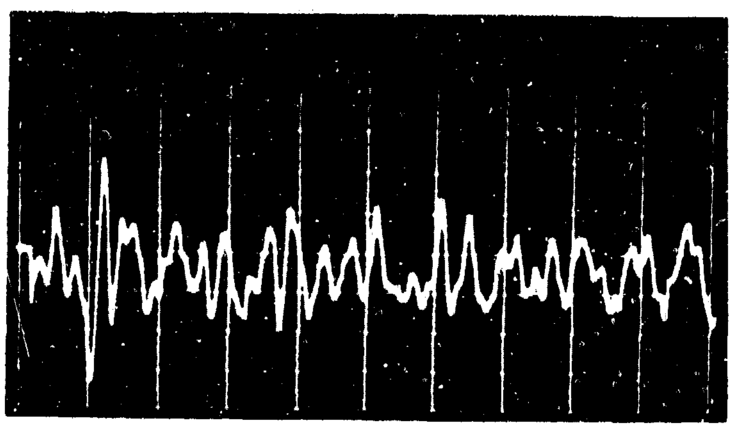
Erector spinae muscle EMG activity was monitored before and after isometric extension fatiguing efforts. Typical EMG amplitude versus time signals are shown in Figures 4 and 5. Note that the beginning signal seems to be much more compressed, indicating a higher frequency than the end signal. Using the Wavetek/Rockland model #5820A spectrum analyzer (Figure 2), one can see in the power spectra (Figures 6 and 7) for these signals that there has indeed been a change in the peak of the spectrum from a higher to a lower frequency. It was this phenomenon of a decrease in the frequency of the EMG signal that was used to monitor muscle fatigue. Since the spectrum analyzer could communicate with a DEC 1123 minicomputer (Figure 2), an algorithm was written to compute the center frequency of the spectrum analyzed between one and two hundred Hertz. This is a single-number evaluation of the EMG spectrum, essentially the frequency at which the centroid of the spectrum area occurs.

Fatigue tests were conducted at one per day at either 80, 60, 45, 37.5, or 30 percent of the subject's initial Maximum Voluntary Contraction (MVC) for that day. A constant force was held until



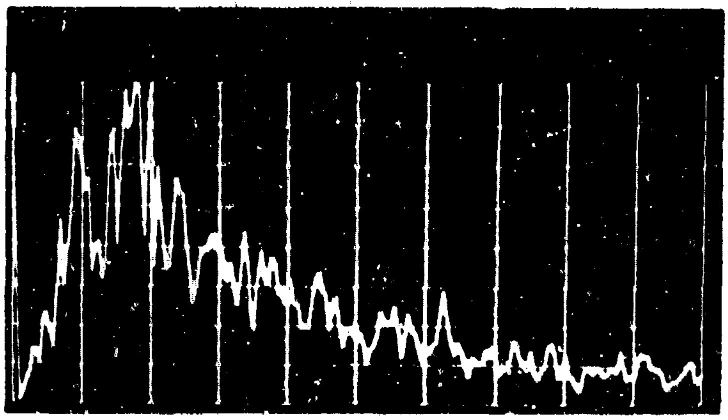
TIME A: 99.99mSEC/
SPAN: 0.000HZ-200.00HZ SN:1.8+00V
FS:±2.5+00V 6.3-01V/

Figure 4. Typical erector spinae electromyographic data plotted with respect to time. These data show the EMG signal at the beginning of a typical lumbar erector spinae isometric extension effort held to exhaustion.



TIME A: 99.99mSEC/
SPAN: 0.000HZ-200.00HZ SN:1.8+00V
FS:±2.5+00V 6.3-01V/

Figure 5. Typical erector spinae electromyographic data plotted with respect to time. These data show the EMG signal at the end of a typical lumbar erector spinae isometric extension effort held to exhaustion.



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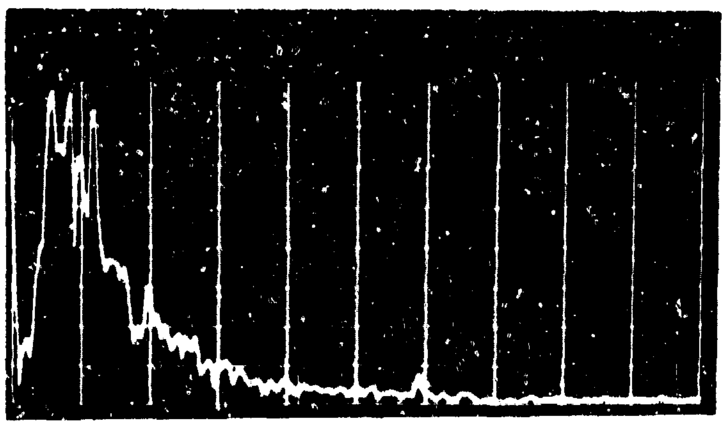
N: 4 ß :1HZ SPAN:0.000HZ-200.00HZ
SN:5.6+00V FS:1.1-01V 1.4-02V/

Figure 6. The frequency components of typical lumbar erector spinae electromyographic data at the beginning of an isometric extension effort.



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N: 4ß:1HZ SPAN:0.000HZ-200.00HZ
SN:5.6+00V FS:1.1-01V 1.4-02V/

Figure 7. The frequency components of typical lumbar erector spinae electromyographic data at the end of an isometric extension effort. Note the shift toward the lower frequencies (toward the left) of the spectrum taken at the end of the isometric extension effort.

exhaustion or until pain interrupted their isometric contraction (Figure 8). In summary, the following protocol was used:

Protocol: 3 maximum voluntary contractions (3 seconds)

80% MVC 5 seconds
2 minute rest

60% MVC 5 seconds
2 minute rest

45% MVC 5 seconds
2 minute rest

37.5% MVC 5 seconds
2 minute rest

30% MVC 5 seconds
10 minute rest

Fatigue effort to exhaustion - at one of above the %MVC levels

Analysis of the EMG signal's spectral activity was determined over a 6-second period at the beginning and end of each fatiguing effort. Using the index counter on a tape recorder and observing recorded EMG signals on an oscilloscope ensured that sampling occurred at the beginning and end of the test period.

Figures 9 through 12 show the results of the decrease in center frequency for the group of 20 subjects. The figures show the statistically significant differences compiled for individual groups by sex for both left and right EMG center frequency decreases.

For all fatiguing efforts, center frequency decreased from the beginning to the end of the test. Comparisons were made between sides for the same sex and between sexes for the same side. The only significant difference (Figure 13) in changes occurred between sexes on each side at the 30% MVC level, where the females decreased

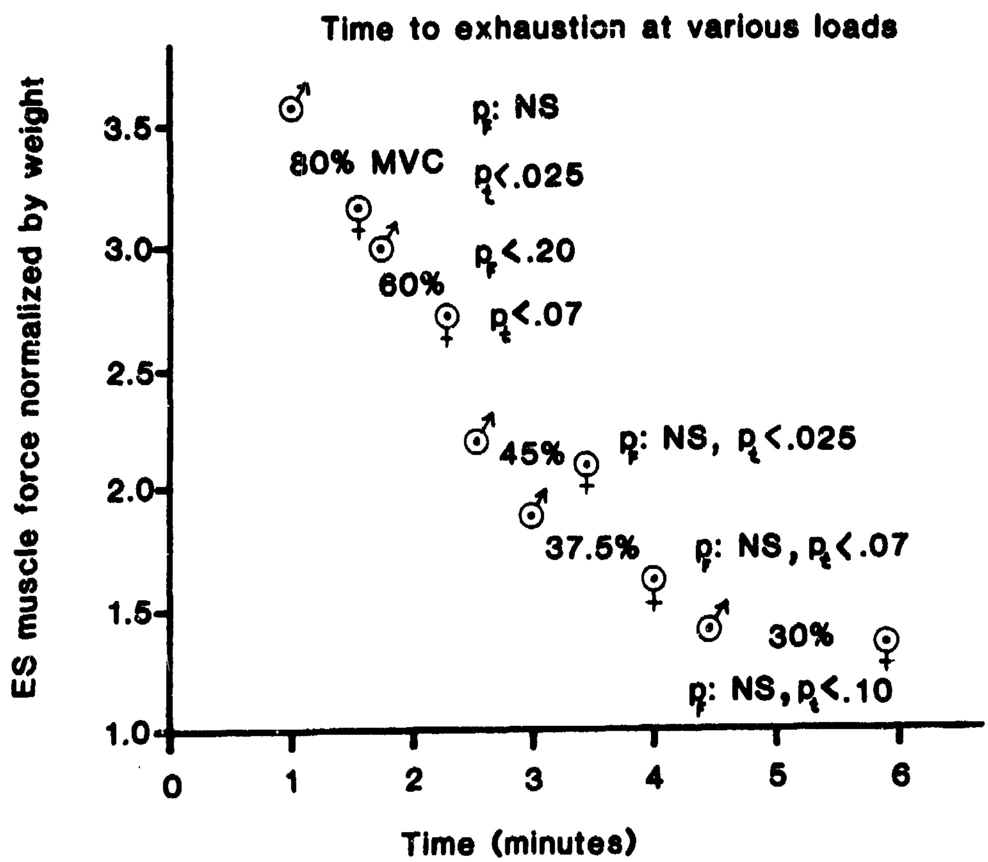


Figure 8. Time duration for which subjects (male and female) were able to maintain various proportions of maximum voluntary contraction extension efforts prior to exhaustion.

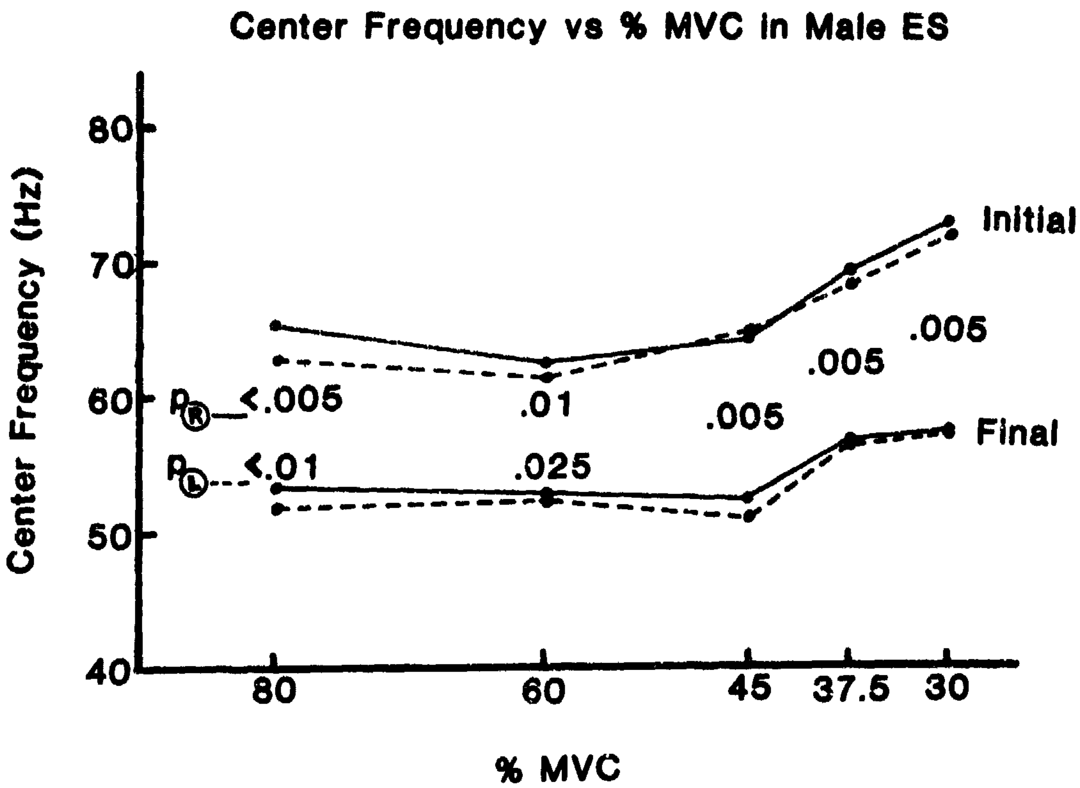


Figure 9. Levels of significance of differences between the initial and final center frequencies of the EMG activities due to various proportions of maximum voluntary contraction fatiguing efforts. There were significant differences at all levels and for both right and left erector spinae muscle groups in the males tested.

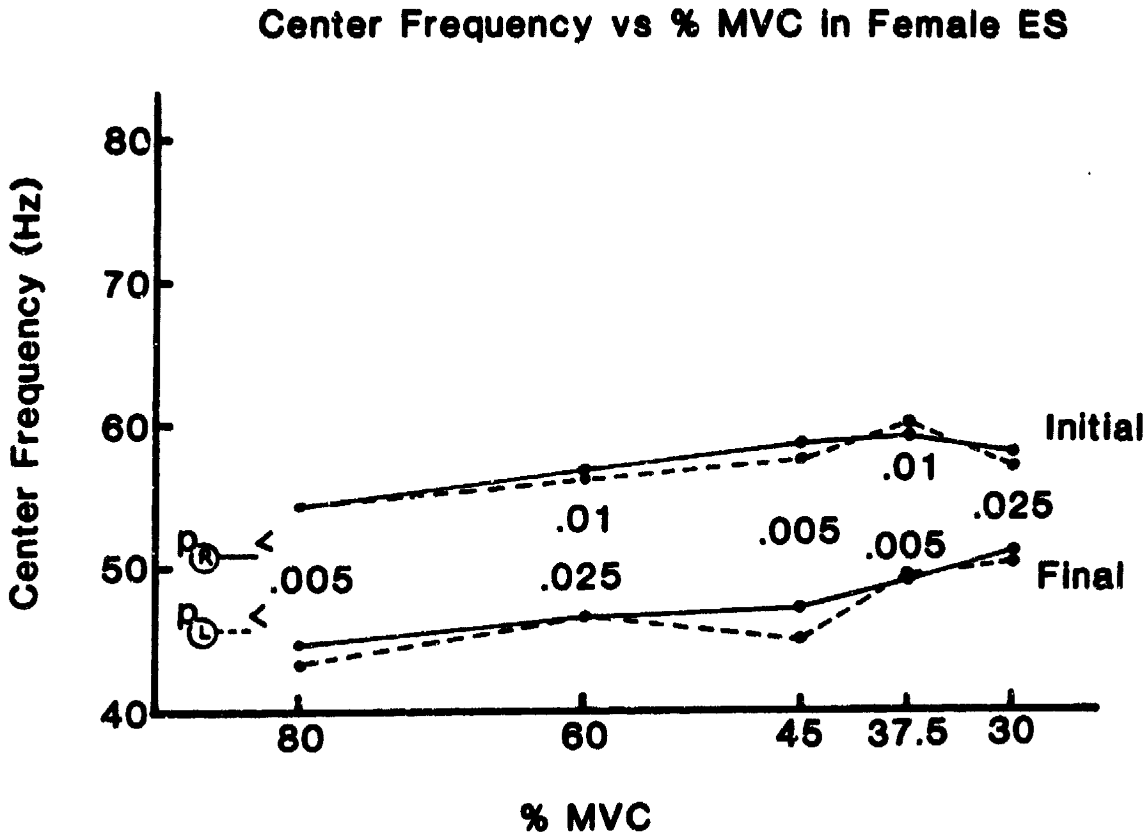


Figure 10. Levels of significance of differences between the initial and final center frequencies of the EMG activities due to various proportions of maximum voluntary contraction fatiguing efforts. There were significant differences at all levels and for both right and left erector spinae muscle groups in the females tested.

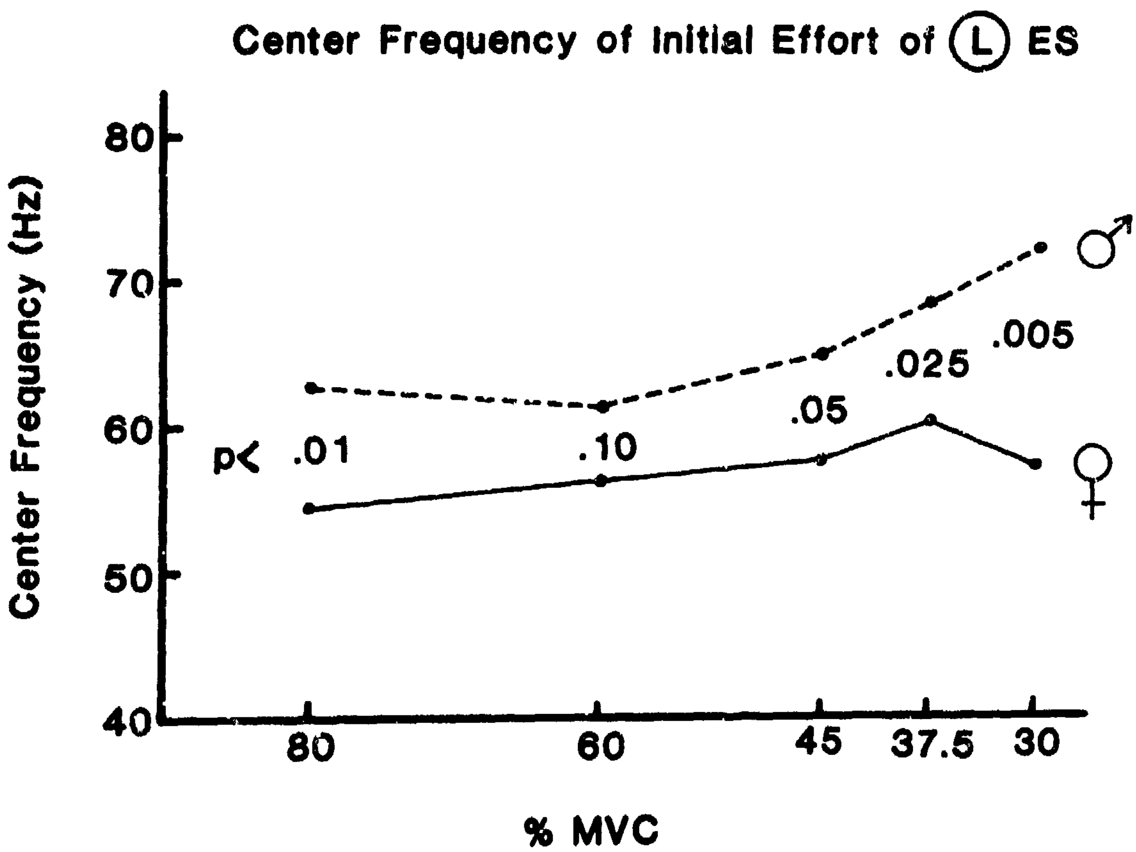


Figure 11. Level of significance of differences in the EMG spectrum center frequencies due to sex for various levels of maximum voluntary contraction isometric fatiguing efforts in the left erector spinae muscle group.

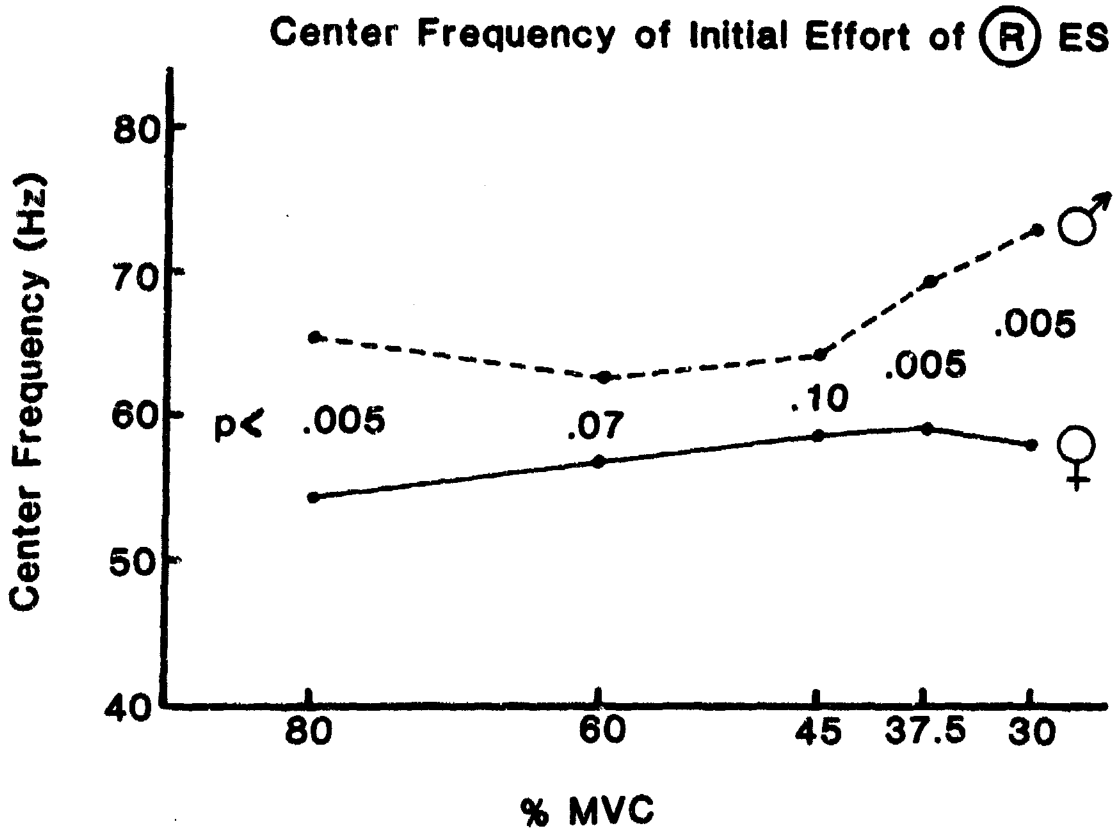


Figure 12. Level of significance of differences in the EMG spectrum center frequencies due to sex for various levels of maximum voluntary contraction isometric fatiguing efforts in the right erector spinae muscle group.

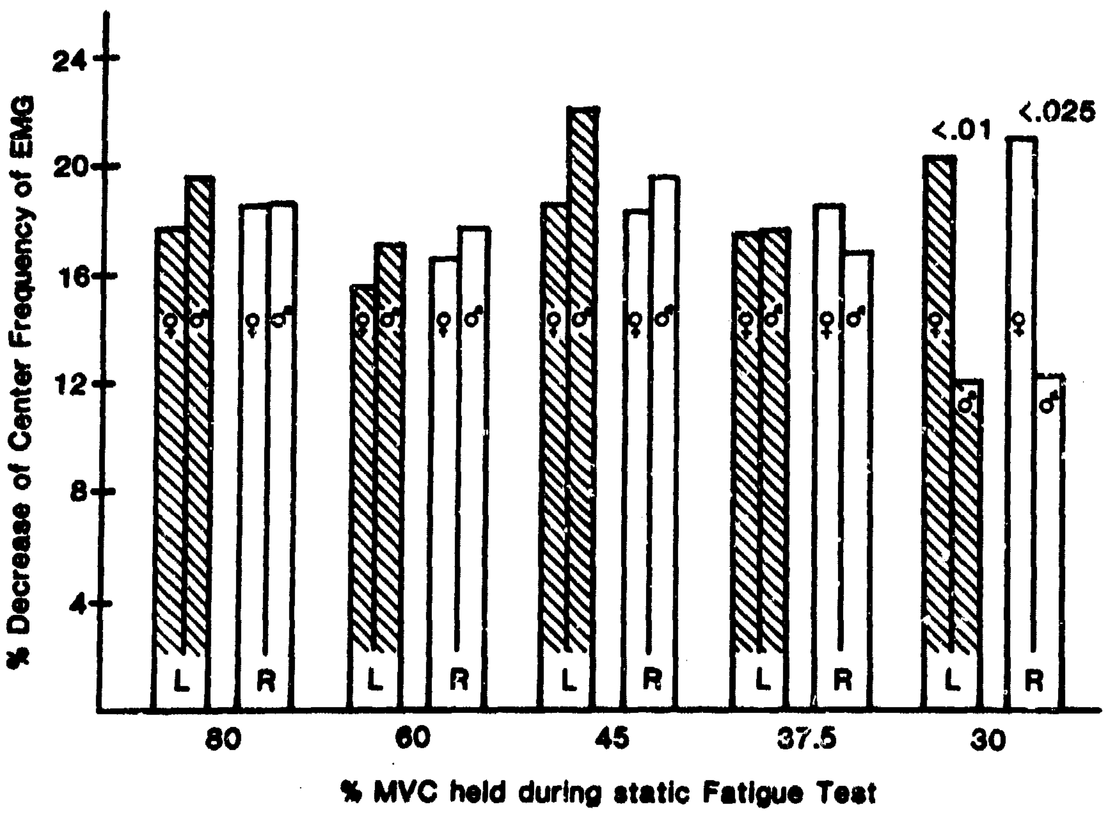


Figure 13. Comparison between sexes of the left and right erector spinae fatigue responses as indicated by the percent decrease in center frequency of the EMG spectrum as a function of proportion of maximum voluntary contraction isometric extension fatigue effort. Only at the 30% MVC level is there a significant difference between sexes.

in activity significantly less. The significance of this study derives from the demonstration that there is no difference in these changes either between sexes for the same side or between sides for the same sex except at the 30% MVC level.

The level of subjective pain felt by the subject in the lower back or buttocks was monitored by the Visual Analog Scale (VAS), Figure 14 (Aitken, 1969; Woodforde and Merskey, 1972). Subjects reported level of pain by making a mark along a 10 cm horizontal line, the anchorpoints of which were designated "No pain" and "Extreme Pain." Measures were taken using the VAS technique before and at eight 15-minute intervals during the static and vibration testing.

4.2 Fatigue Due to Mechanical Vibration

Vibration experiments were conducted with the use of a custom-made vibration simulator. A Rexroth Corporation 30-hp hydraulic power supply delivered pressure to a servo actuator valve which was driven by a single loop displacement feedback servo controller. Flight vibrations were monitored and recorded by USAARL using an Endevco Model 4815A Triaxial accelerometer mounted at the seatpost in the cockpit of the UH-1H aircraft. Individual axes of accelerometer recordings were used to drive the servo hydraulic system which reproduced the actual flight vibrations (Figure 15). System response was fine tuned by matching accelerometer outputs on the spectrum analyzer with those from the actual recordings sampled during the flight of a UH-1H helicopter.

Because of the unique design of this vibration simulator, studies using individual axes of vibration could be conducted because the

Visual Analogue Scale

No Pain Excruciating Pain

Time: _____

Please indicate on the line the amount of pain you are presently experiencing. The left hand side represents NO PAIN while the right hand end represents EXCRUCIATING.

Figure 14. Visual Analog Scale used in the study.

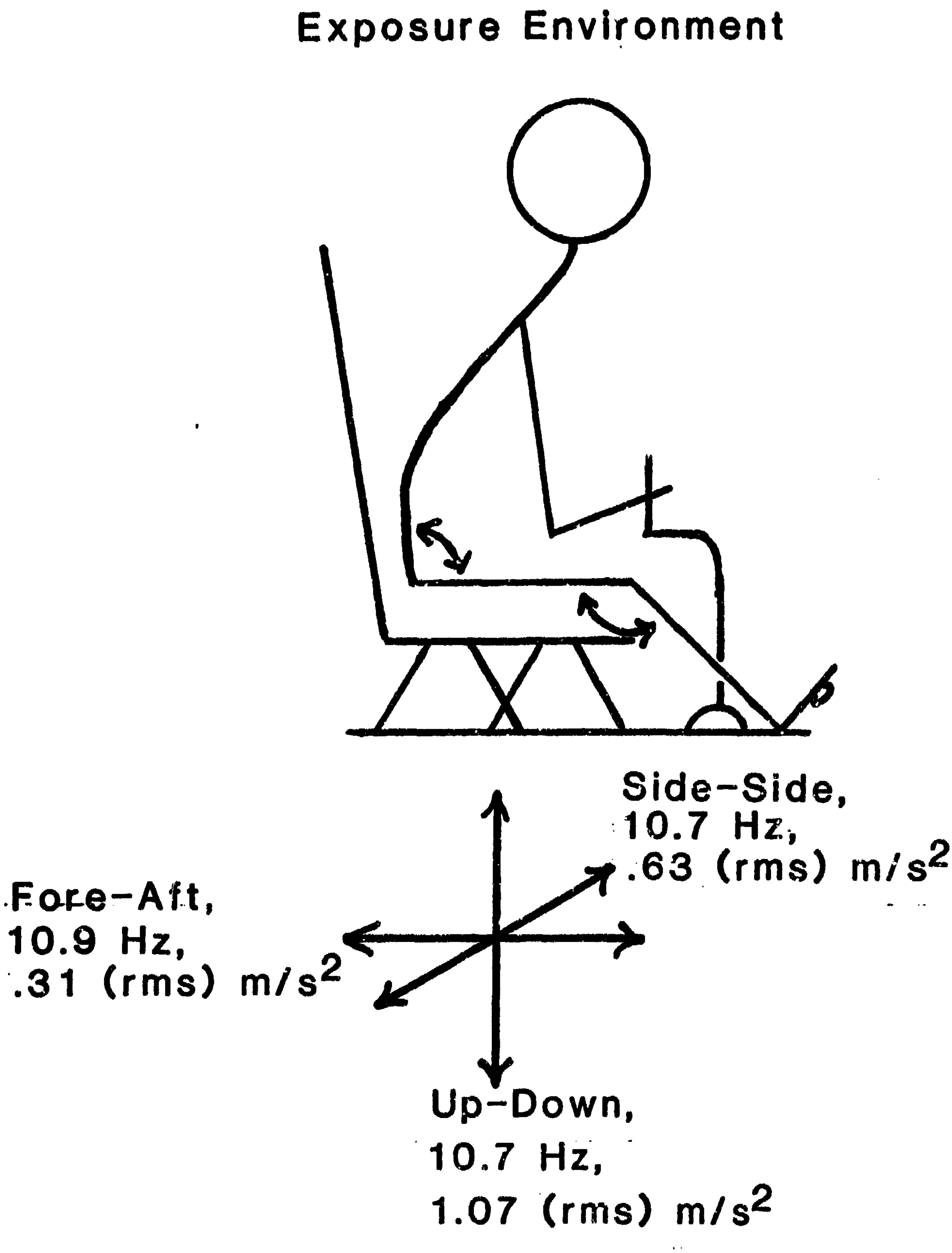


Figure 15. Main acceleration and frequency components of the UH-1H specific vibration environment for each of three axes.

actuator was mounted to a pivoting axis. An adjustable cable system was used to support the helicopter seat/cockpit platform for two of the three axes of vibration experiments (Figures 16-18). This cable system allowed the platform to hang suspended and vibrate in a horizontal plane while being vertically supported (i.e. fore-aft, side-to-side experiments, Figures 17 and 18). Modification of the vibration simulator was required in the up-down axes (Figure 16), which allowed the platform to be vibrated in a vertical direction while supported on a rickshaw-like framework in the horizontal axes.

In the experiments, two accelerometers were used to measure bite bar acceleration and seat platform acceleration. A Schaevitz model LSQBV accelerometer was securely mounted below the vibration simulator platform next to the driving end of the actuator. This was used for monitoring the output acceleration of the platform on which the seat was mounted. A bite-bar accelerometer, furnished by USAARL, contained an ENTRAN model EGAL accelerometer (Figure 19). To monitor driving point impedance, a load cell was mounted between the servo-hydraulic actuator and the seat platform.

A sine-sweep series of experiments were performed by inputting a ramp signal into a sine-wave generator to produce a linear sweep output from 0 to 20 Hz over a 20-minute period.

4.3 Fatigue Assessment Using Change in the Back Surface Motion Behavior in a Vertical Vibration Environment

Change in the shape of the back surface was used as an outcome measure of the effect of UH-1H specific vertical vibration on the

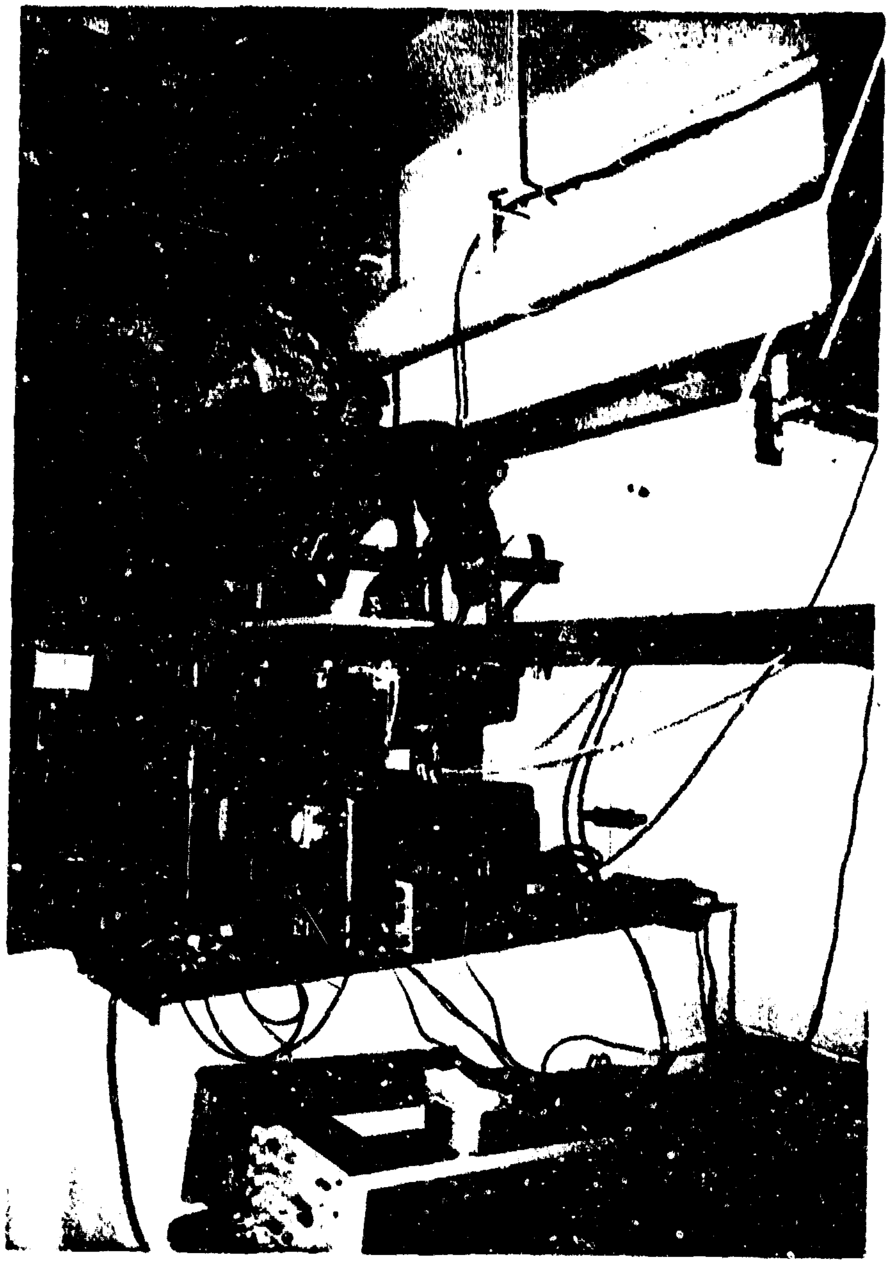


Figure 16. UH-1H cockpit seating environment in an Up-Down vibration mode. Note the stabilizing supports protruding from the front of the seat platform.

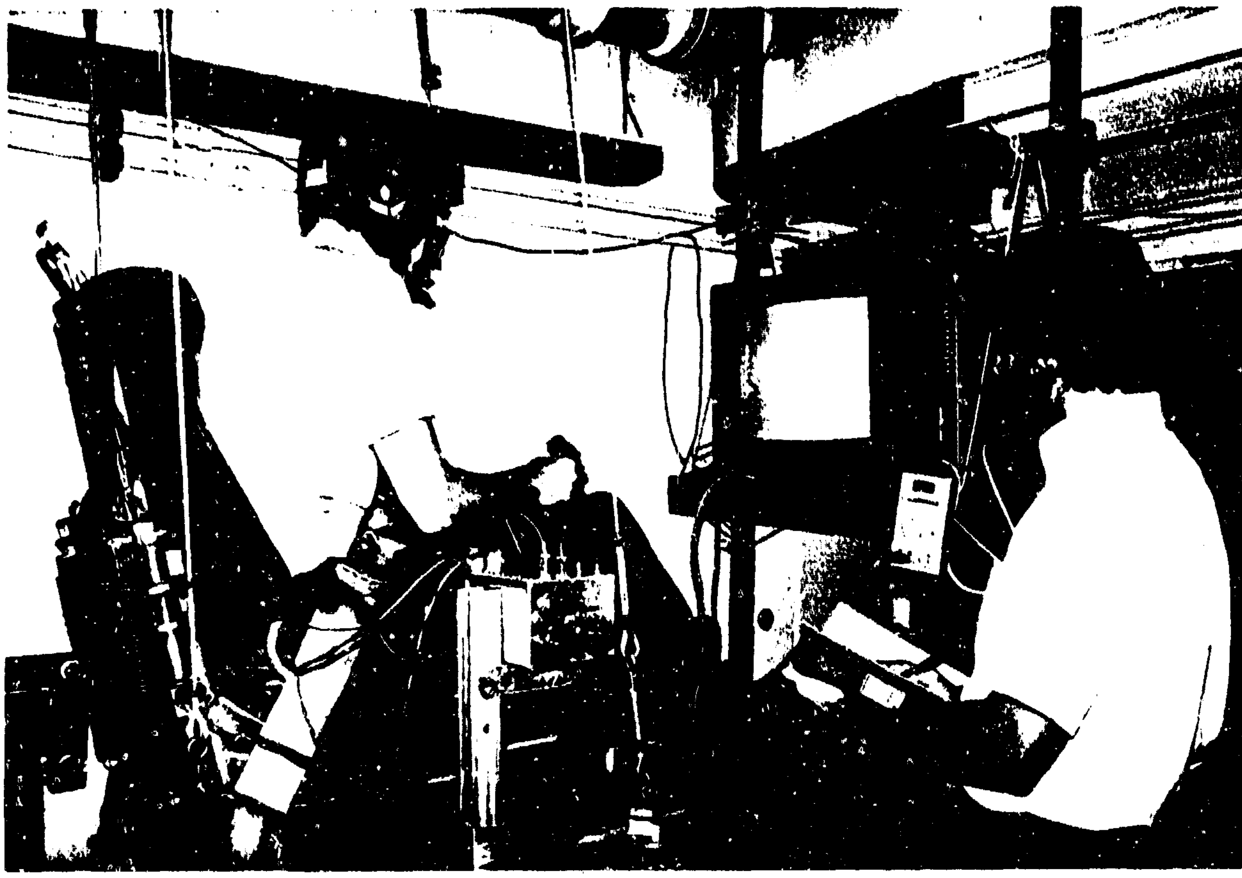


Figure 17. UH-1H cockpit seating environment oriented for testing in a Fore-Aft vibration mode. Seat platform is hung from the ceiling by four cables. Note the "Space Invaders" game on the television. The defensive action in the game provided via the UH-1H control stick.

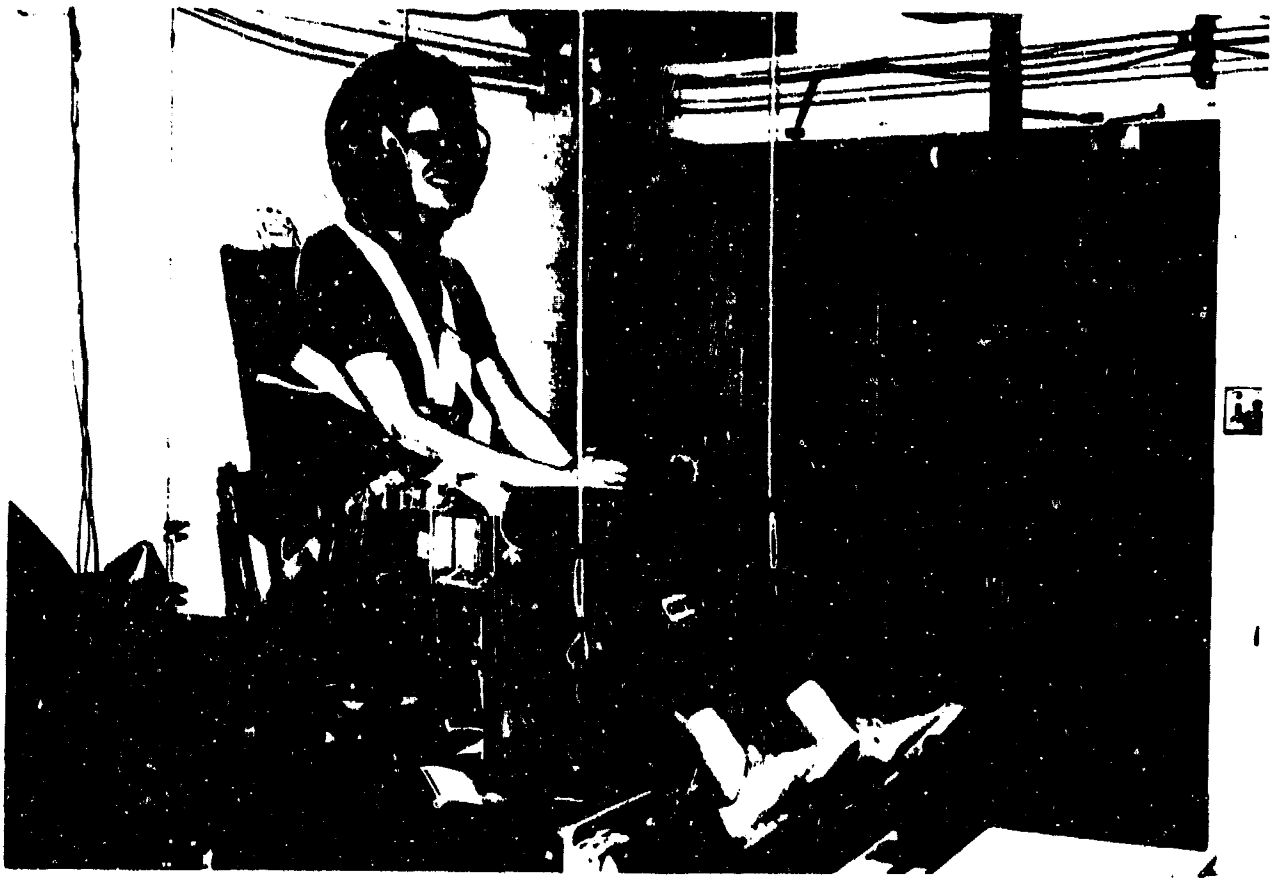


Figure 18. UH-1H cockpit seating environment oriented for testing in a Side-to-Side mode.

Figure 19. Test subject with bite bar accelerometer in position. This accelerometer was used to compare acceleration at the head to that input at the seat/platform interface.

seated operator. Change of shape was defined as the standard deviation of the amount of motion that occurred at discrete markers located on the back as the subject was vertically vibrated at his first natural frequency. The shape change in this experiment was more an assessment of the ability of the trunk muscles to maintain an unsupported upright seated posture before and after two hours of vertical vibration in the slumped asymmetric posture typical of the UH-1H pilot.

Five male subjects were tested for their back surface motion changes before and after exposure to UH-1H seated vertical vibration. On each subject, markers were placed on the skin (Figure 20) of the back over the spinous processes along the spine and also over each scapular prominence. Around each scapular marker were located other markers above, below, to the right and to the left.

The subject's seated response to vibration was assessed in the following manner. The subject sat upright in the UH-1H seat and was held in place by the seat (lap) belt. Since the seat back had been removed, there was no support for the back, thereby forcing the subject to maintain his posture by muscle control. The seat was vertically vibrated using a sine wave generator-driven servo-hydraulic shaker (peak to peak displacement, of 3.2 mm (1/8 inch). The frequency of vibration was adjusted between 4 and 6 Hz until a maximum acceleration was found at the accelerometer placed on top of a hockey helmet worn by the subject. Once the subject's first natural frequency was found, the helmet was removed and a series of 10-20 paired photographs (according to the data needs of photogrammetry) were taken of the back using two motor-driven 35

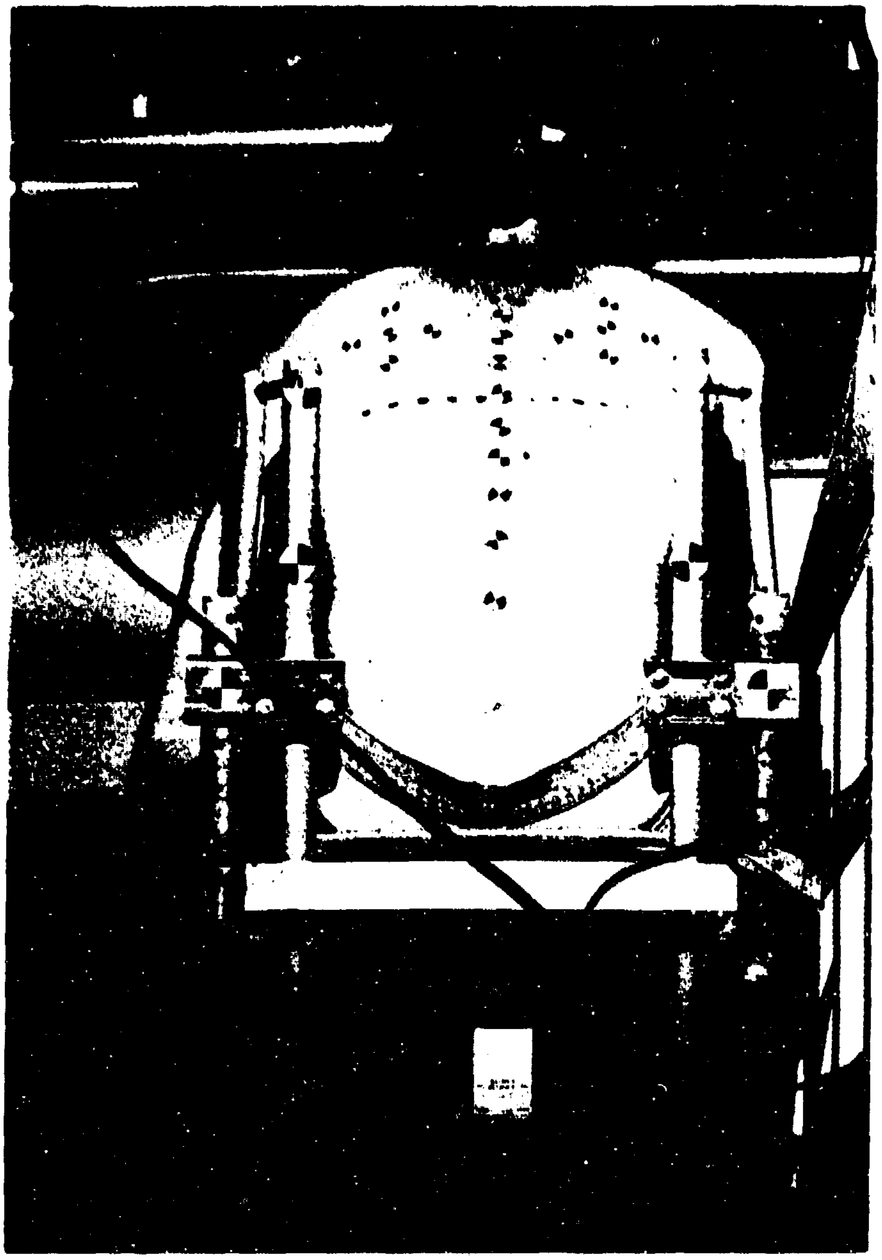


Figure 20. "Straight-on" view of a subject's back, prepared for evaluation of its surface motion characteristics due to two hours of UH-1H specific vertical vibration. Note lack of back support due to need for clear view of back surface.

mm cameras. The cameras were placed some horizontal distance apart and could "see" the same marker points on the back surface (Figures 21 and 22). Also as required by the stereo photogrammetry technique (Stokes, 1982; Marzan, 1975), the cameras were set to make their exposures simultaneously. Since it was not possible to "fire" the cameras at a frequency two times or more of that at which the subject was vibrating, they were "fired" randomly. It was assumed that the randomly-taken pictures would provide enough data to allow a description of the full range of motion (in three dimensions) of each point through a cycle of vibration.

After the pre-test pictures were obtained, the subject assumed the typical flight posture (Figure 23) of the UH-1H pilot: sitting forward with both feet on control pedals and both hands on the appropriate control sticks, while being subjected to the UH-1H specific vertical vibration. Post-test back surface motion data were collected in a fashion similar (Figures 24 and 25) to the pre-test method while using the same vertical vibration input as in the pre-test.

Photographic data were then analyzed using established photogrammetry techniques (Stokes, 1982) for determining the spatial coordinates of each point on the back while the body was in each position. The final analysis performed found the mean and standard deviation of the position of each point in space over all the positions (10-20 pre-test positions and 10-20 post-test positions). The magnitude of the standard deviation of each point's position change reflects the amount of deviation from the average of all the positions; hence, it reflects the motion of the point.

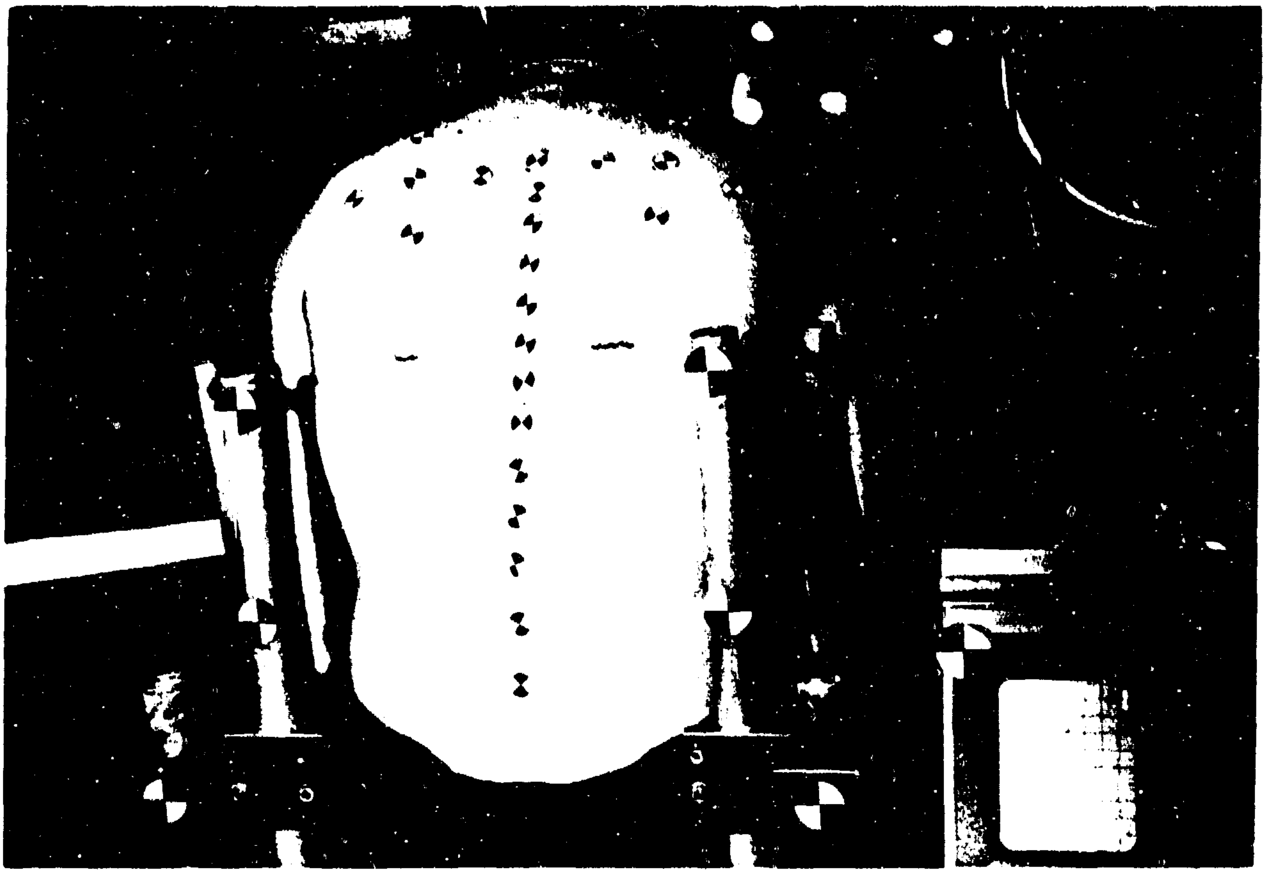


Figure 21. View from the right camera of a subject's back before exposure to two hours of UH-1H specific vertical vibration.

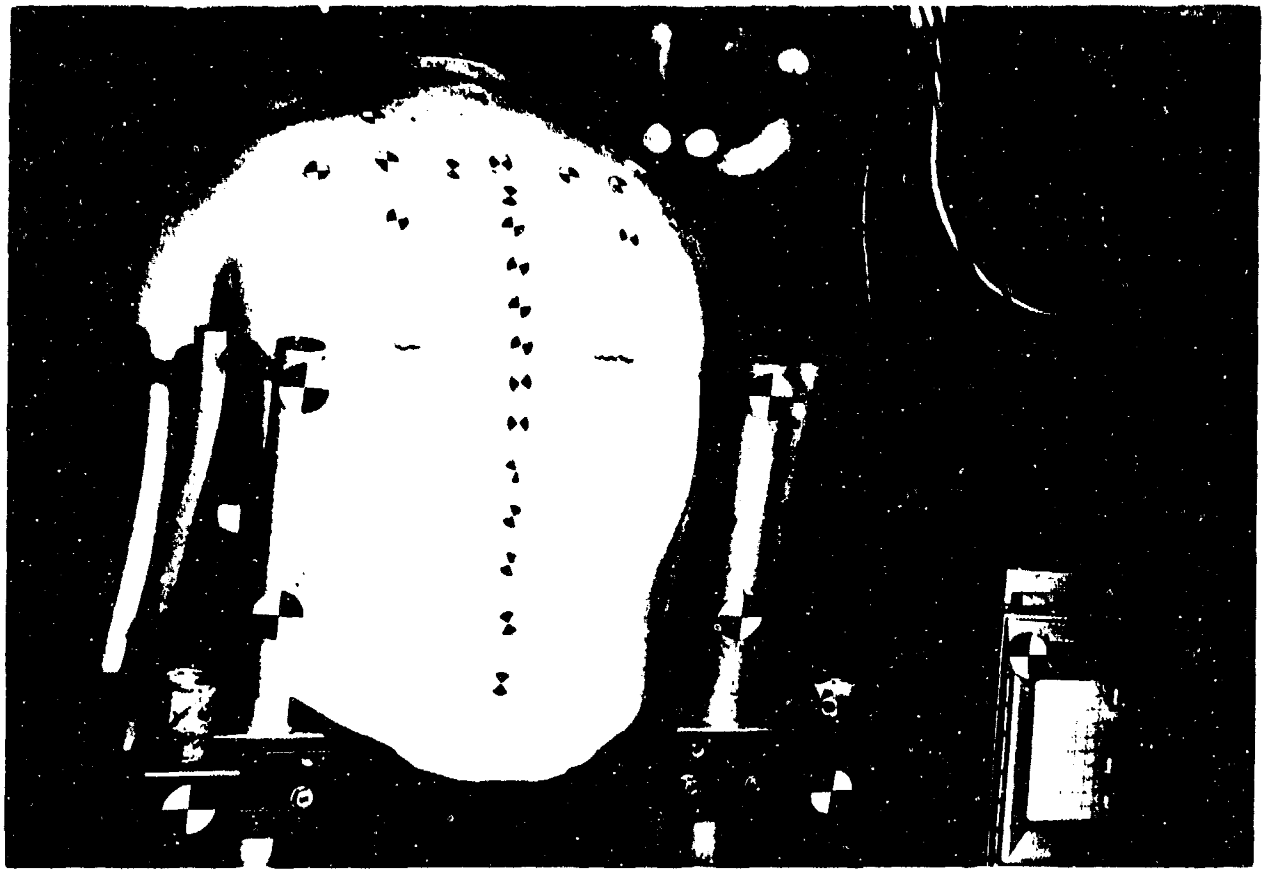


Figure 22. View from the left camera of a subject's back before exposure to two hours of UH-1H specific vertical vibration.

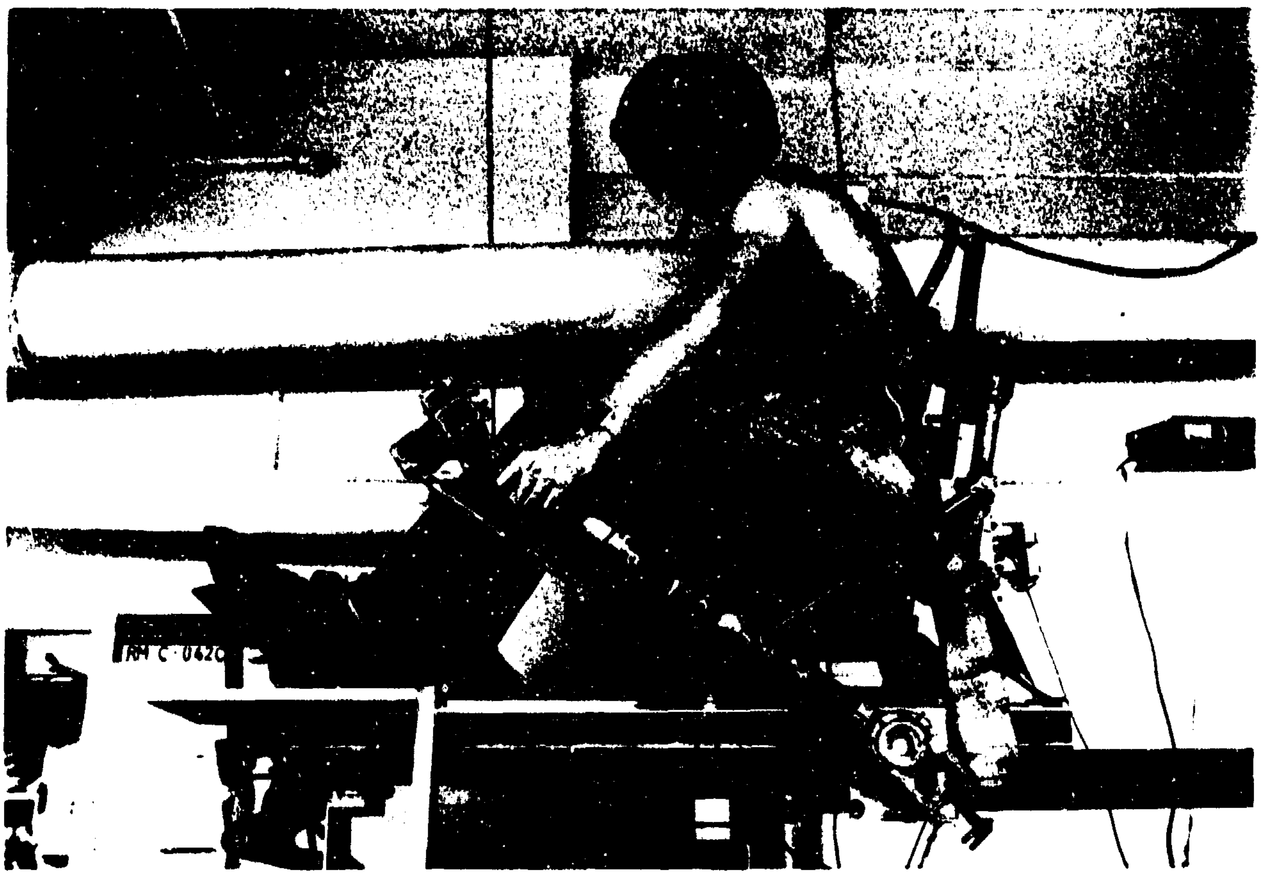


Figure 23. Posture held by subject during two-hour exposure to UH-1H specific Up-Down, Side-to-Side, or Fore-Aft vibration. In this case, the back support was removed for photogrammetric surface analysis.

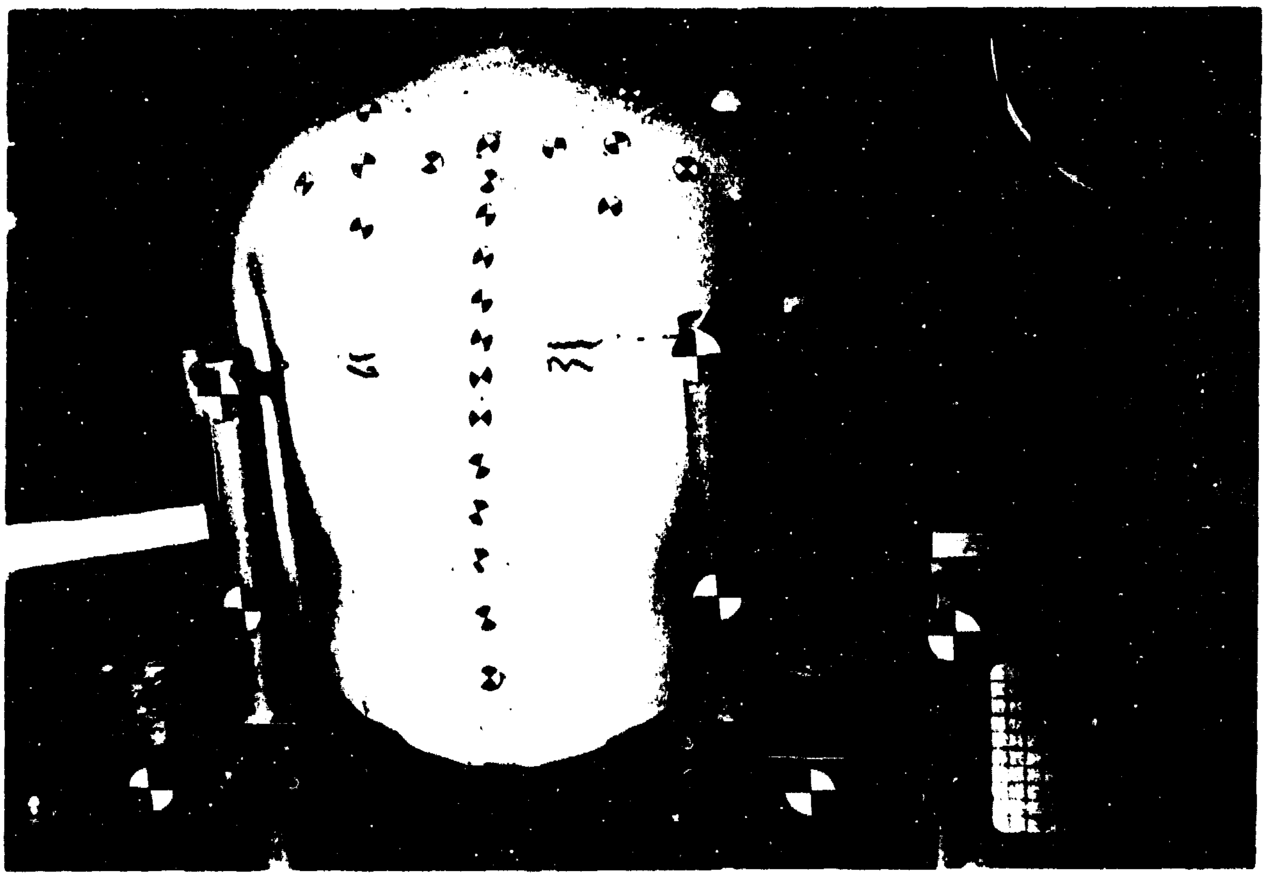


Figure 24. View from the right camera of a subject's back after exposure to two hours of UH-1H specific vertical vibration.

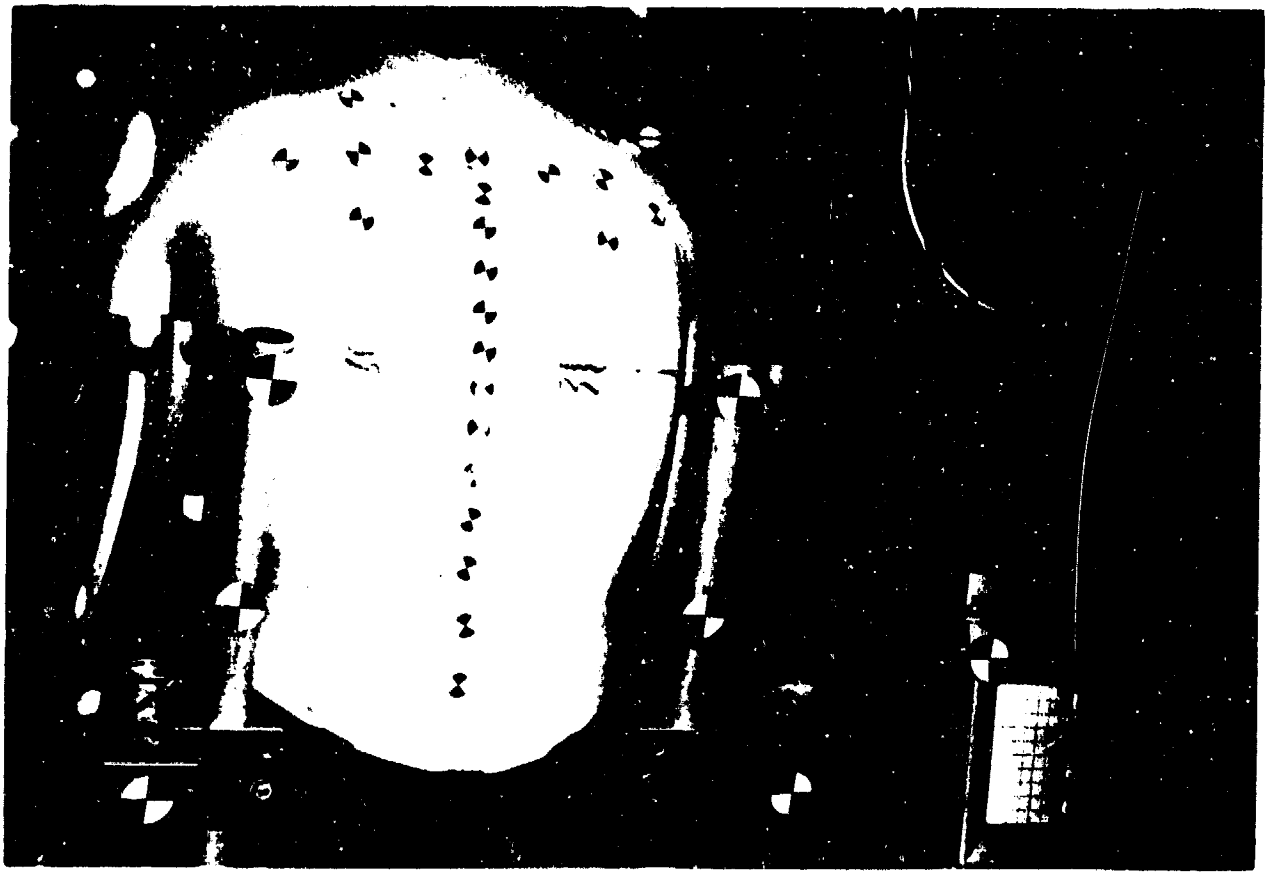


Figure 25. View from the left camera of a subject's back after exposure to two hours of UH-1H specific vertical vibration.

4.4 Seating Test Protocol

4.4.1 Static UH-1H Cockpit Seating Tests

Subjects were seated in the UH-1H seat and adjustments were made in seat height and distance to pedals in order to conform to the standard flight position of pilots (Figure 23). After placement of electrodes on the back, EMG signals were monitored to observe that their amplitude and gains were adjusted to display an amplitude suitable for recording. Subjects were instructed in how to grasp the cyclic and collective and were told that they could remove the left hand from the collective for one minute every half hour. Instrumented into the cyclic were the controls for an Atari video game, which subjects were instructed to use in order to concentrate on a "mission" (Figure 17).

One maximum voluntary extension effort (Figure 26) was performed in the test set-up to establish a 60% MVC contraction level to be used prior to and at the end of the two-hour seating test. The chest harness used for horizontal loading was the same as that used in the isometric fatiguing effort study (section 4.1). It was removed during the two-hour seating test. The two-hour test period began when initial EMG signals were recorded (time = 0). Recordings were then made every 15 minutes for a total of nine samples. Also recorded was the time of onset of pain and level of pain at onset and at 15-minute periods thereafter, using the visual analog scale (VAS) technique (Aitken, 1969). At the conclusion of two hours, the harness was reapplied and the 60% MVC was held briefly (5 seconds).

Figure 26. Subject performing a 60% maximum voluntary contraction extension effort to quantify muscle EMG activity before or after exposure to two hours of UH-1H specific vibration.

Protocol: Maximum Voluntary Contraction extension effort (MVC) - 60% MVC for 5 seconds

Sample EMG - time (min): 0, 15, 30, 45, 60, 75, 90, 105, 120

Record onset of pain and intensity of pain
60% MVC for 5 seconds

4.4.2 Vibration UH-1H Cockpit Seating Tests

Twenty subjects were tested for a two-hour period on three different days in each mode of uni-axial vibration (up-down, fore-aft, side-to-side; Figures 15-18). EMG activity was recorded from the left erector spinae musculature and acceleration data were recorded from a bite bar accelerometer located on the mouthpiece and an accelerometer mounted to the vibration simulator platform next to the actuator piston driving the seating system.

The protocol described for the static seating tests was followed throughout the two-hour vibration seating tests. Subjects were seated in the UH-1H seat and adjustments were made to the seat height and distance to foot pedals to conform to the standard flight position of pilots (Figure 23). Subjects were instructed in how to grasp the cyclic and collective and were told that removal of the left hand from the collective was allowed for one minute every half hour. Subjects were instructed in the operation of the cyclic which had been instrumented to control the Atari video computer (Figure 17).

Prior to vibrating, a maximum voluntary contraction (MVC) was performed to establish a 60% MVC level to be used prior to and at the end of the two-hour tests. The chest harness was put on for the initial 60% MVC loading, removed during the two hours of vibration and reapplied for the final 60% MVC test. To ensure accurate

calibration of the two accelerometers, a cross channel spectrum analyzer was used to monitor each output. The mouthpiece accelerometer was clamped to the same plate as the platform accelerometer and outputs adjusted before the experiment. Four channels of data were recorded during the test: two channels of acceleration (bite bar and platform), left erector spinae activity and reaction force at the actuator-platform interface. Approximately every 15 minutes, data were sampled for a total of nine samples over each two-hour period. The accelerometer bite bar was only inserted into the subject's mouth at the data-gathering points at 15-minute intervals to avoid fatigue of the mandible. Also recorded was the time of onset of pain and the initial level of pain, as indicated by the subject on a visual analog scale (VAS). Remaining 15-minute time periods were monitored for changes in intensity of pain on the VAS.

Vibration Protocol:

MVC, pause, then 60% MVC for 5 seconds

Start two-hour vibration exposure

Sample EMG, force and acceleration signals

(time (min): 0, 15, 30, 45, 60, 75, 100, 120)

Record onset of pain and intensity of pain via VAS

60% MVC for 5 seconds

The vibration flight protocol consisted of two hours' exposure to each axis of vibration as recorded in the UH-1H by the U. S. Army Aeromedical Research Lab. At least two weeks were allowed between testing each axis of vibration. The two hours of vibration consisted

of four take-offs and landings with each "flight" lasting 30 minutes (Figure 27).

Vibration "Flight" Protocol:

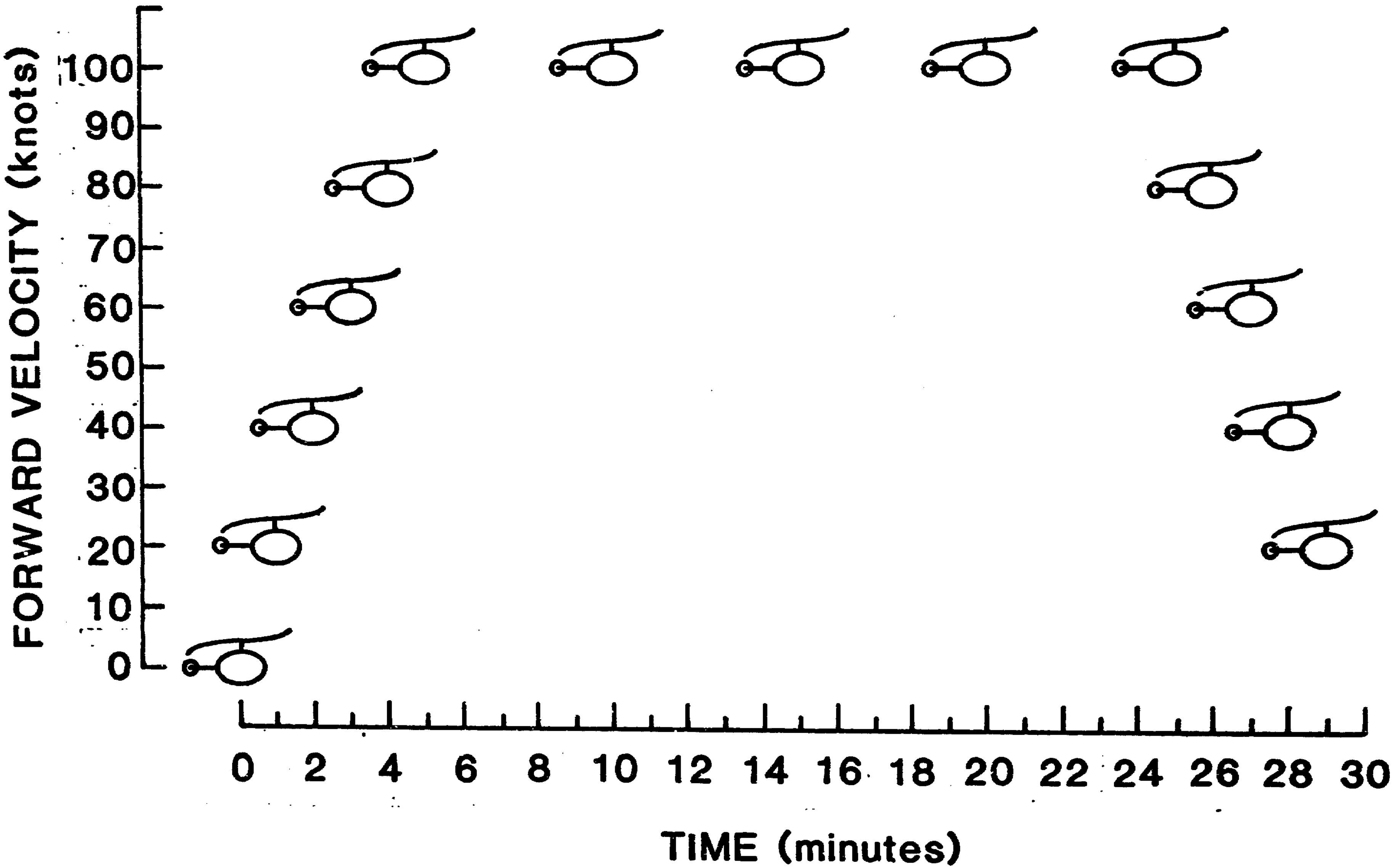
0-1 minutes	Engine running
1-2	Hover
2-4	Hover to 100 knots
4-26	Cruise at 100 knots
26-28	100 knots to hover
28-29	Hover
29-30	Engine running

5. RESULTS AND DISCUSSION

5.1 Fatigue Assessment Using Change in Center Frequency of Erector Spinae Electromyography Spectrum and Visual Analog Discomfort Scale

Due to motion artifact, it was not possible to discern a difference in the EMG data obtained during the vibration tests. Hence these data could not be used as an index of fatigue or as a transfer function with respect to muscle response to driving vibration.

However, there were differences in the EMG center frequency of the EMG signal when comparing the lumbar musculature's pre-test activity to its post-test activity during a 60% maximum voluntary contraction effort (Figures 28 through 30). The only marginally significant ($p < .07$) difference (with respect to initial activity),



HELICOPTER FLIGHT PROFILE

Figure 27. Forward velocity versus time "mission" profile used four times for each two-hour UH-1H specific vibration exposure.

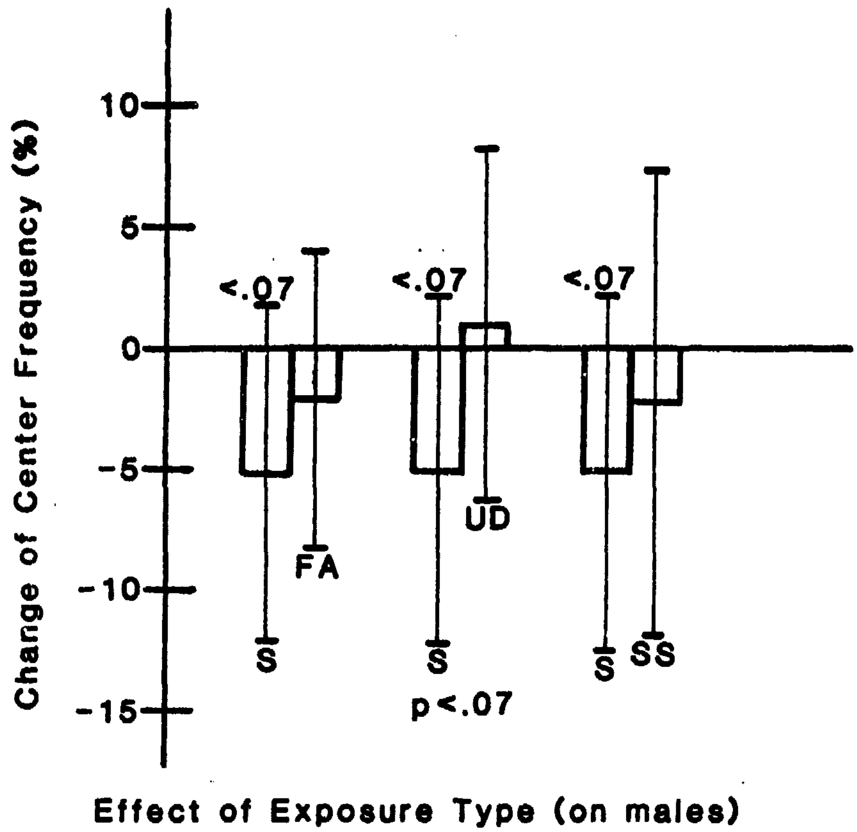


Figure 28. Effect of (S) Static Sitting, (FA) Fore-Aft, (UD) Up-and-Down, and (SS) Side-to-Side vibration exposures on males. There was a marginally significant effect due to static sitting exposure and a marginally significant difference between static sitting and up-and-down vibration exposures. No other exposures or differences were significant.

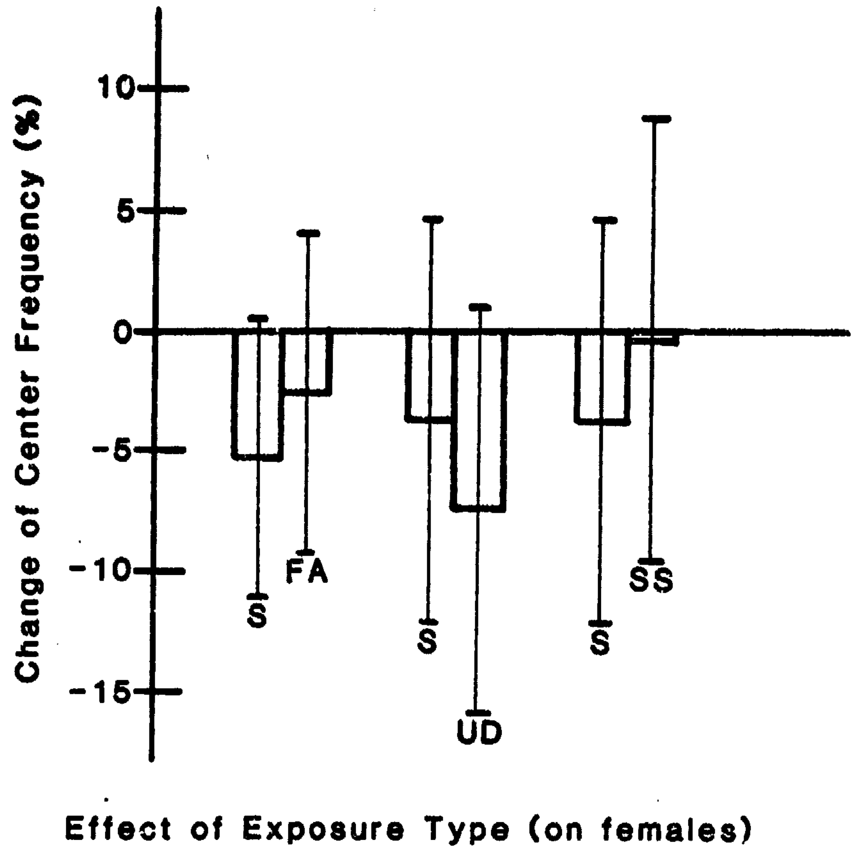


Figure 29. Effect of (S) Static Sitting, (FA) Fore-Aft, (UD) Up-and-Down, and (SS) Side-to-Side vibration exposures on females. There were no significant changes due to any exposure, nor were there any significant differences between static sitting and any vibration exposure.

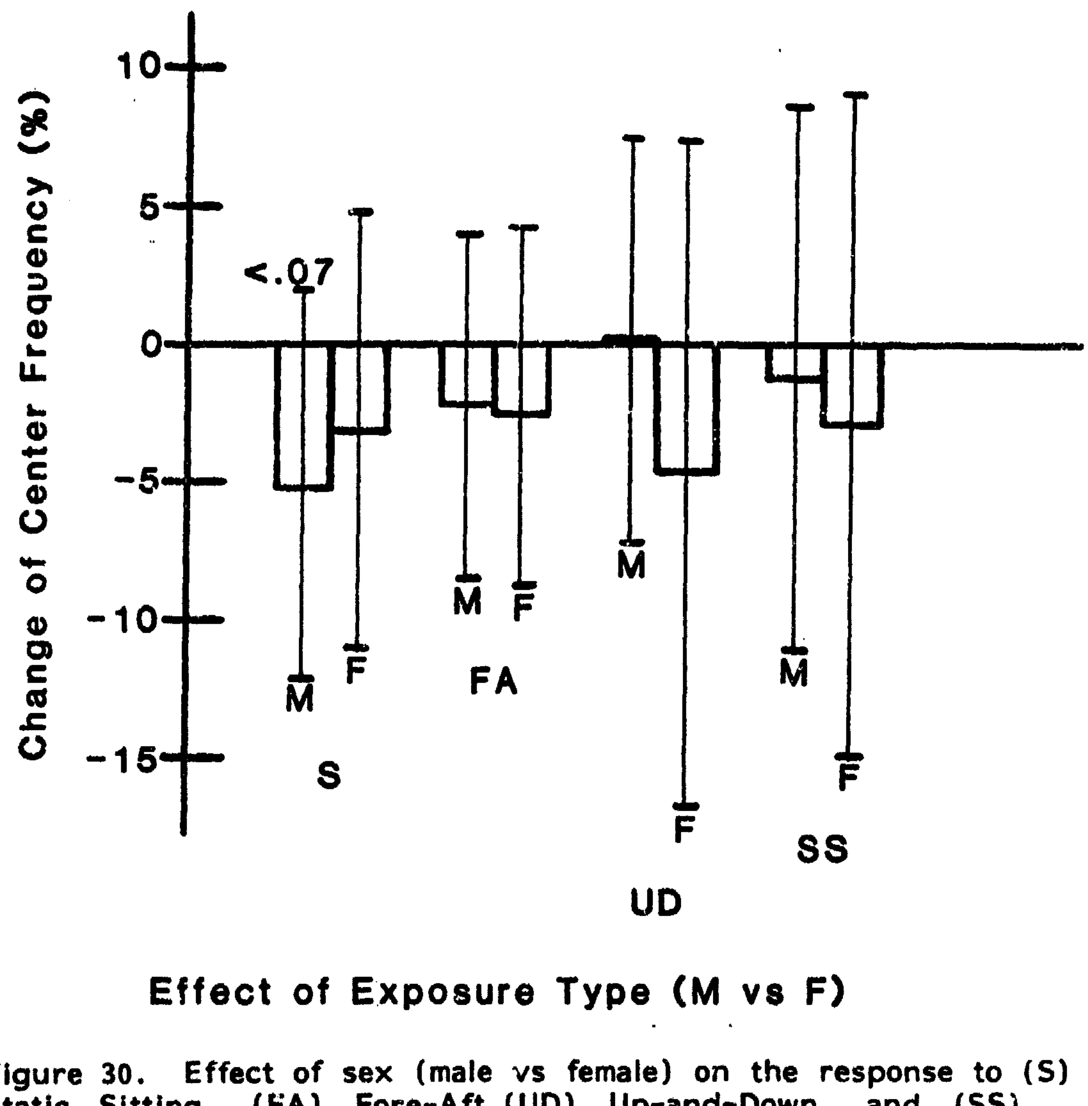


Figure 30. Effect of sex (male vs female) on the response to (S) Static Sitting, (FA) Fore-Aft,(UD) Up-and-Down, and (SS) Side-to-Side vibration exposures. Only males had a marginally significant response to static sitting. There were no significant differences due to sex.

however, occurred in males (Figure 28) maintaining the static posture typical of the UH-1H pilot. As can be seen, the percent change in EMG spectrum center frequency was greater than that due to any of the vibration exposures. The only marginally significant ($p < .07$) difference was between the static posture and the up and down vibration in the males (Figure 28).

The subjective pain response of all subjects to two-hour exposure to static posture or seated vibration (Figures 31-34) was both increasing with time and highly significant. When comparing changes, either within or between sexes (Figures 35 and 36), the only significant differences in the changes were found in the males (Figure 35), comparing pain due to static posture with pain due to up and down vibration ($p < .05$) and side-to-side vibration ($p < .025$). Except when compared with pain in females due to fore-aft vibration, the static posture always created more pain.

In reviewing the objective and subjective variables involved in fatigue and pain responses to the sustained static and vibrating UH-1H specific seating environment, it is apparent that the posture maintained is the more significant factor. It must be kept in mind that the subject/pilot is slumped forward, a posture in which the back is not well supported by the back of the seat. In addition, the UH-1H vibration frequency is approximately two times greater than the upright seated operator's vertical natural frequency and approximately seven to ten times that of the fore-aft and side-to-side natural frequencies (ISO, 1978). The mismatch of driving to natural frequencies may be another reason for the lack of effect of the vibration.

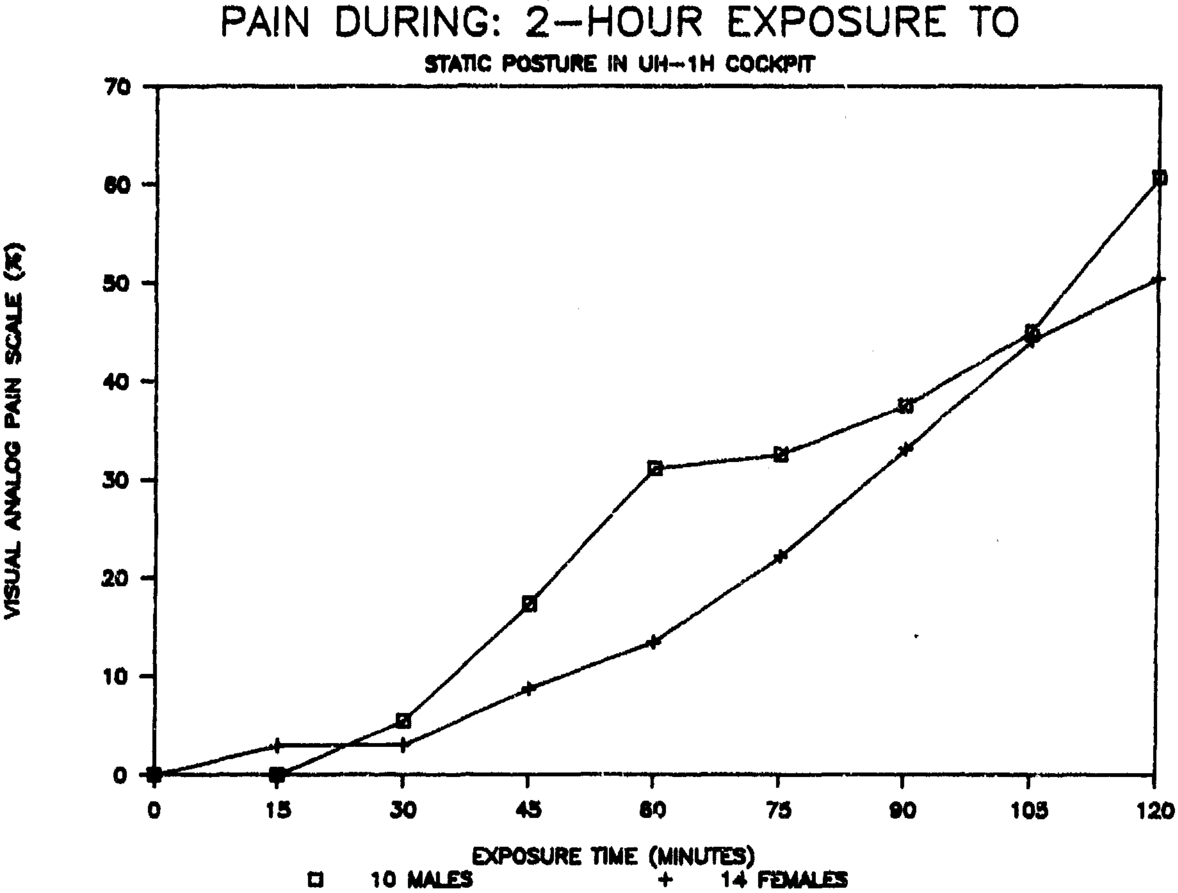


Figure 31. Pain increase over time for males and females exposed to Static Sitting.

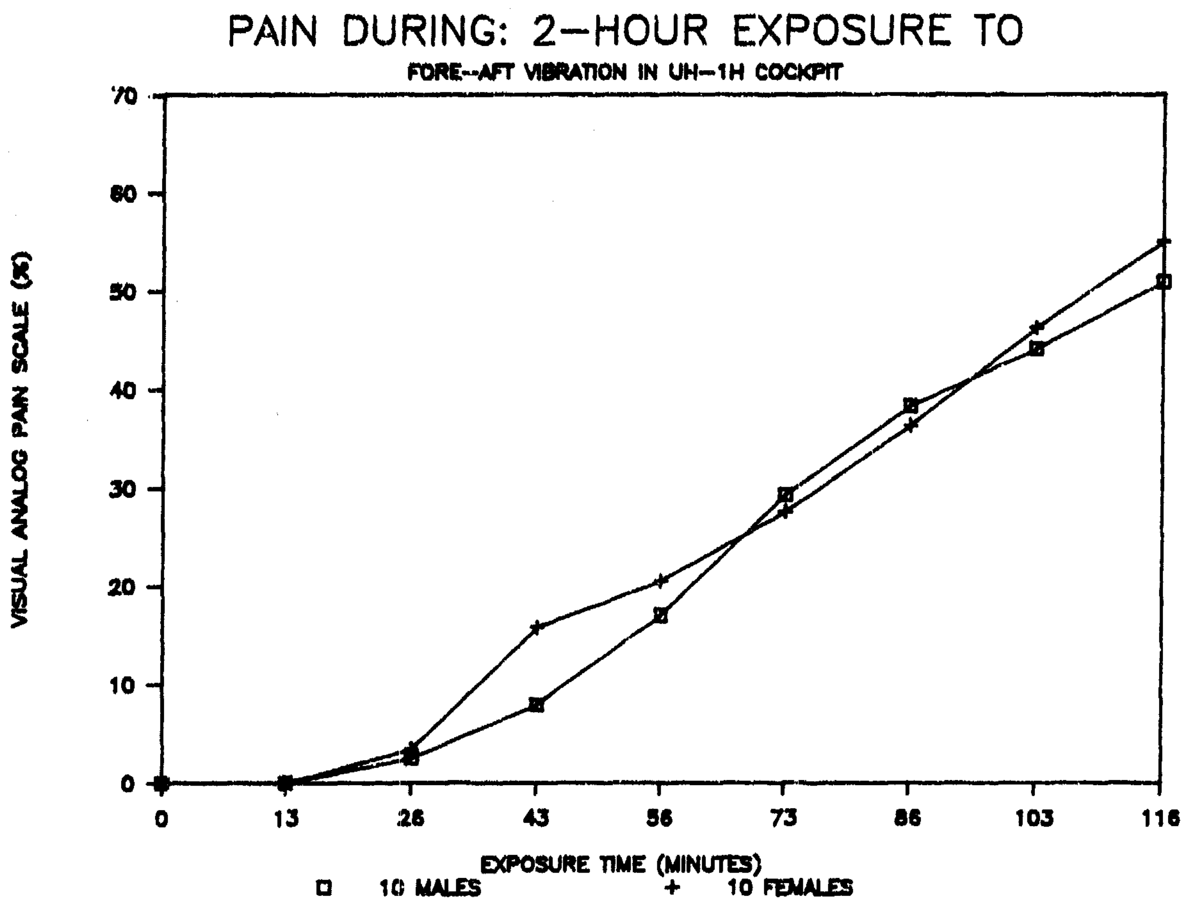


Figure 32. Pain increase over time for males and females exposed to Fore-Aft vibration.

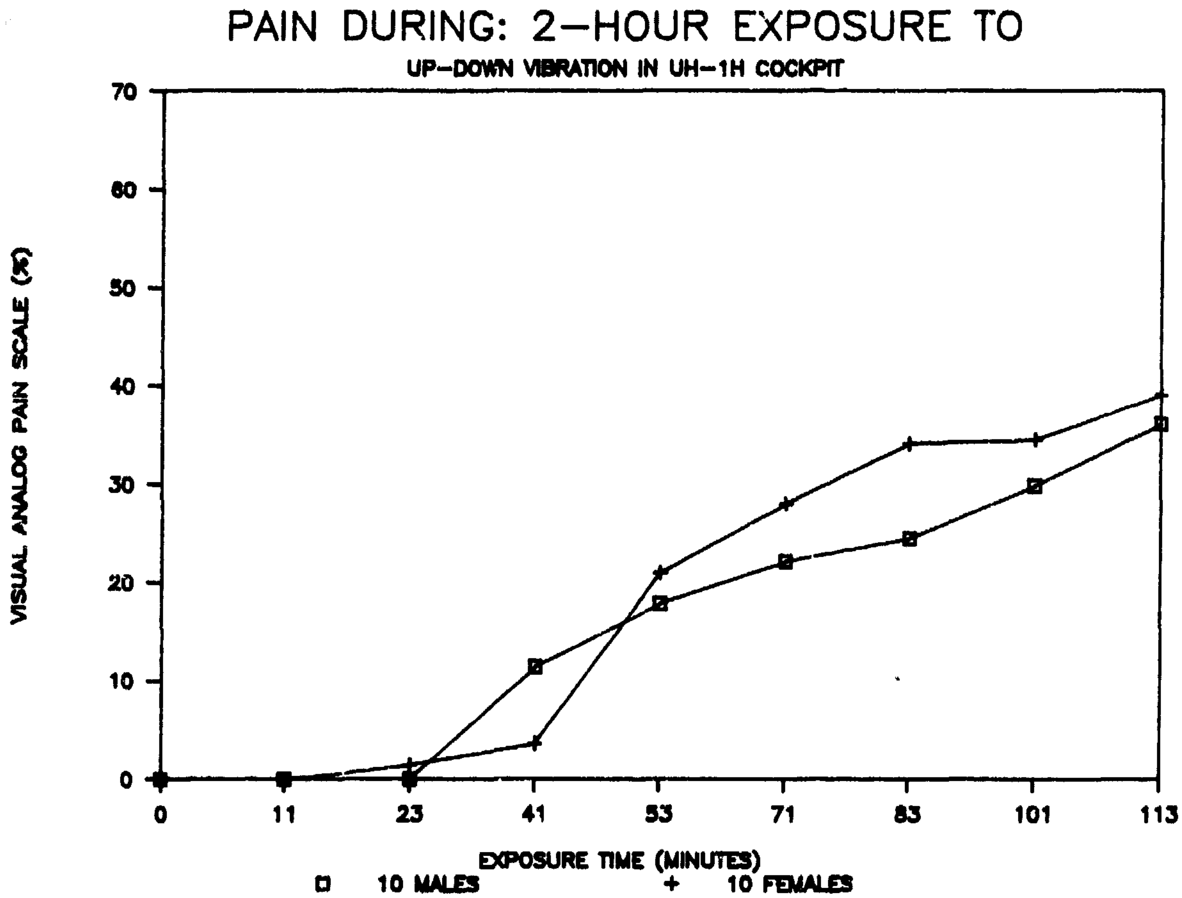


Figure 33. Pain increase over time for males and females exposed to Up-and-Down vibration.

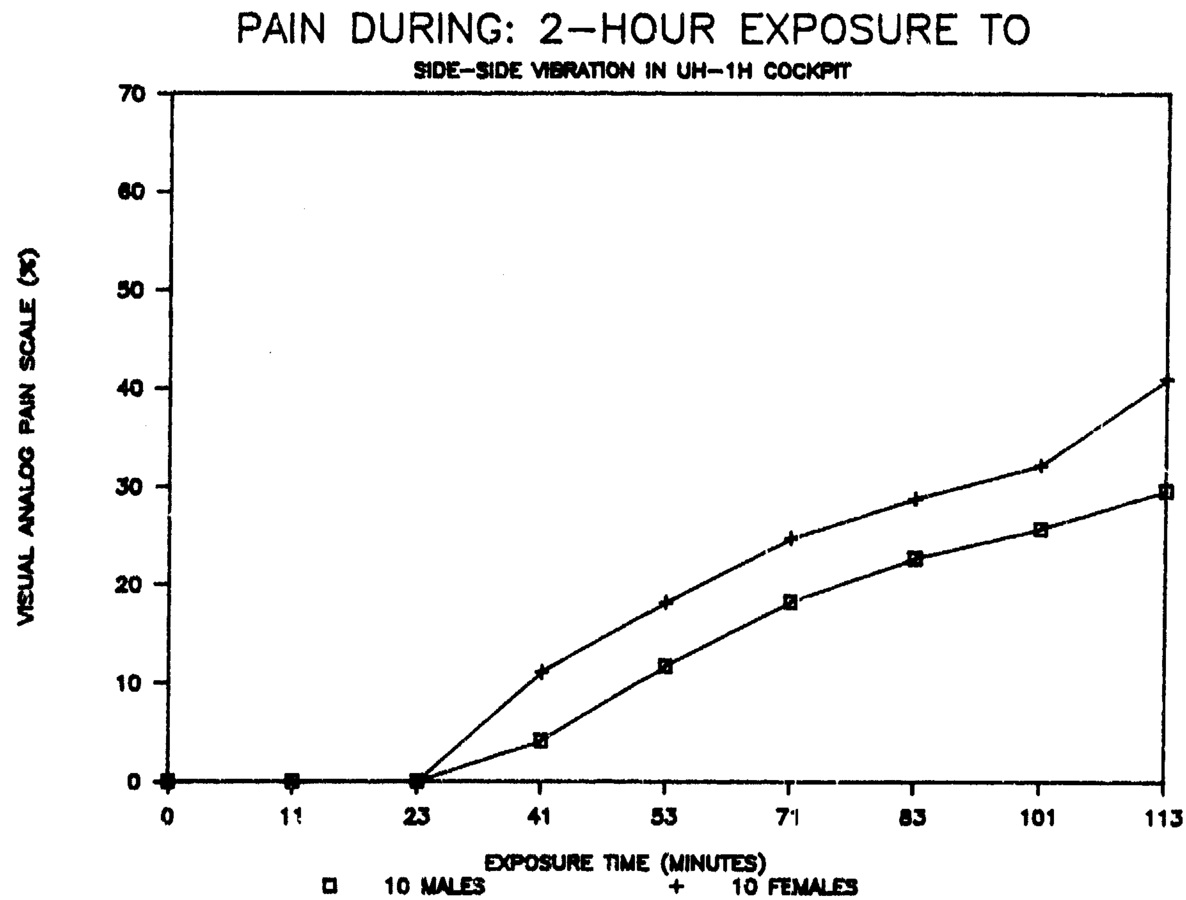


Figure 34. Pain increase over time for males and females exposed to Side-to-Side vibration.

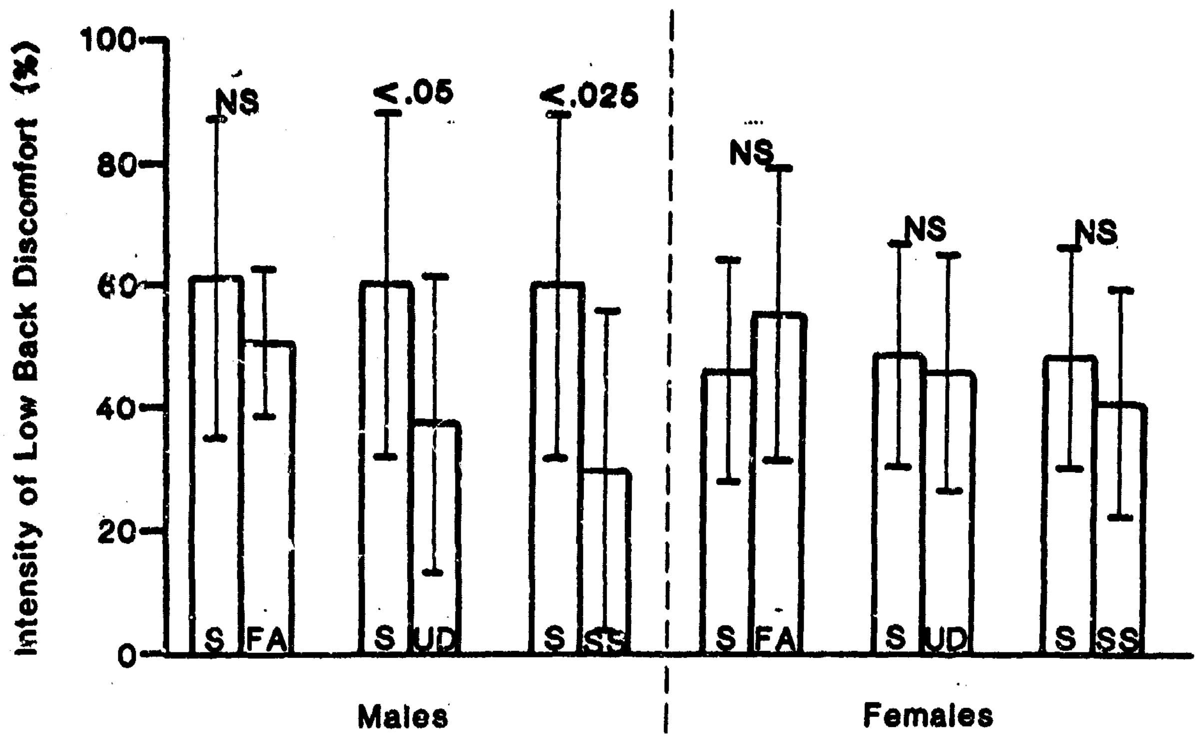


Figure 35. Intensity of low back pain during (S) Static sitting, (FA) Fore-Aft, (UD) Up-and-Down, and (SS) Side-to-Side vibration exposures. All final levels of pain are significantly different from the initial levels. Only males showed significant differences between pain due to static sitting, up-and-down and side-to-side exposures.

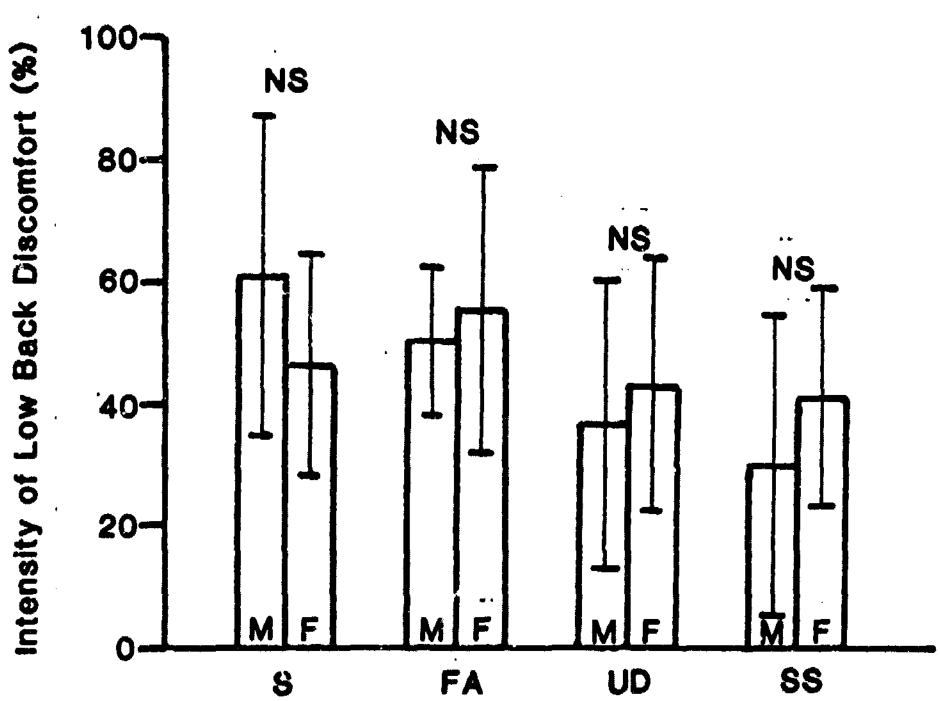


Figure 36. There were no significant differences between sexes at the final levels of pain for each exposure type.

Onset of pain occurred sooner in this study than did onset of pain in the study by Shanahan and Reading (1984). Levels of pain for males were comparable to the Shanahan and Reading study in up-and-down and side-to-side vibration. The males in this study exhibited greater pain than those in the Shanahan and Reading study in fore-aft vibration and static sitting. This may be due to a difference in the scales used or a difference between civilian and military personnel.

According to Keegan (1953), as one sits, the lumbar curve flattens. Schultz et al. (1982) have shown significant increases in intervertebral disk loads with only slight increases in load held in the hand (an increase of flexion moment). The studies of Schultz et al. (1979) and Tencer and Ahmed (1981) also show that the lumbar motion segment responds differently when its facets have been removed. Thus, if the facet joints open up due to a flexed posture (e.g., sitting down), it is likely that more of the load and stability requirements are shifted to the disk. In her epidemiological work on acute herniated lumbar disks, Kelsey (1975) found an association between sitting and the relative risk of acute herniation of a lumbar disk. Finally, Andersson et al. (1974; 5 studies) have performed extensive work studying the effect of seated posture on the lumbar erector spinae muscle activity and on disc pressure and have shown that a reclined, supported posture (extension) minimizes both.

5.2 Mechanical Vibration Data

5.2.1 Review of the Data Reduction Procedure

The procedure for reducing the vibration data is shown in Figure 37. For each two-minute segment, three frequency functions are computed by the spectrum analyzer:

(1) the mechanical impedance, defined by the transfer function of the seat acceleration (input) and the seat reaction force (output);

(2) the transmissibility, defined by the transfer function of the seat acceleration (input) and the bite bar acceleration (output);

(3) the EMG transfer function, with the seat acceleration as input and EMG activity as output.

The phase and magnitude of the transfer functions are computed by the spectrum analyzer for 0-20 Hz at 0.1 Hz intervals.

These transfer functions are sent from the spectrum analyzer to the DEC MINC microcomputer over an IEEE bus, and are then stored on floppy disks. Using software written in BASIC, the MINC also controls the spectrum analyzer over the IEEE bus. The procedure for computing and storing one transfer function from one two-minute segment is as follows:

(1) the tape is started;

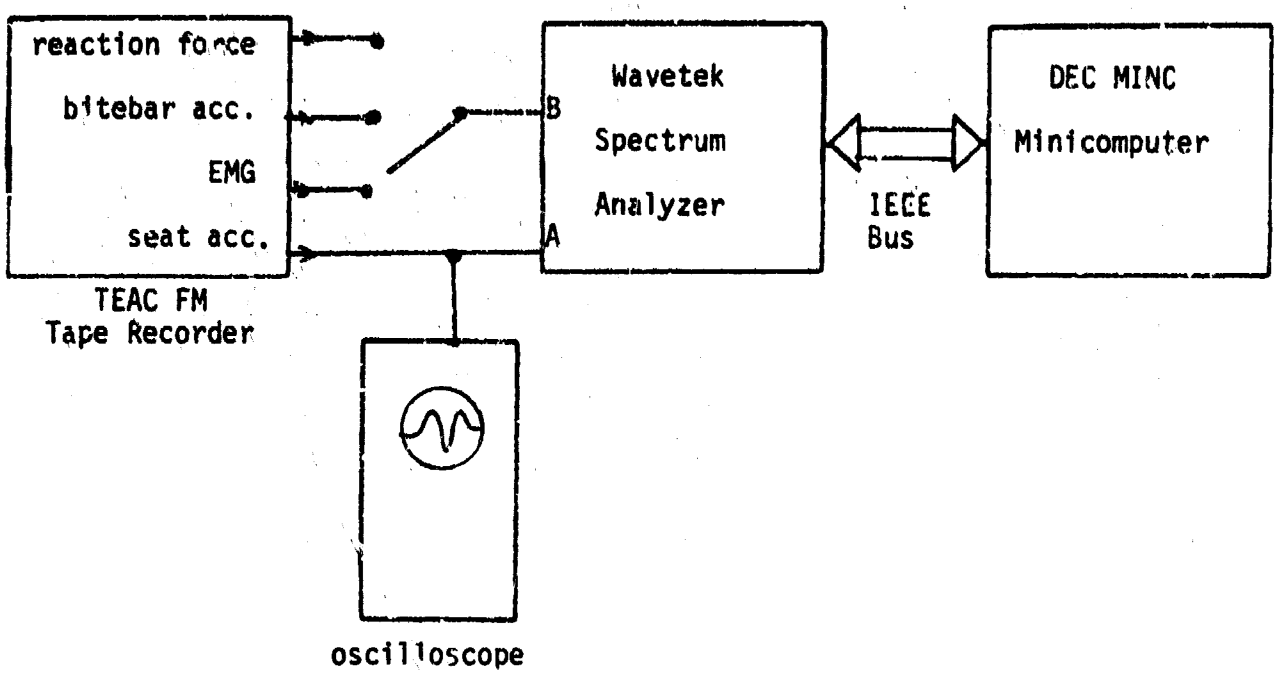


Figure 37. Data Reduction Procedure for the UH-1H Vibration Data. The Minicomputer Controls the Wavetek Spectrum Analyzer and Receives the Computed Transfer Functions over the IEEE Bus.

(2) once the oscilloscope shows the segment has started, the spectrum analyzer is activated by hand;

(3) once the spectrum analyzer has finished computing the transfer function, the computer receives a transfer function phase and magnitude and resets the spectrum analyzer.

5.2.2 Non-valid or Non-interesting Data

The original test matrix involved three transfer functions times three axes of vibration for 10 male and 10 female subjects. Instrumentation problems and some incomplete individual data sets made it more appropriate to analyze only nine males and nine females. During the data reduction phase of the project, it was also found that some of the data did not provide additional insights into the physical system or did not have an acceptable signal-to-noise ratio. These data include (1) the EMG transfer function (with respect to the driving vibration), (2) the impedance transfer function and (3) the side-to-side mode of vibration. These are discussed in turn.

The EMG transfer function was abandoned because unacceptable motion artifacts are caught in the EMG signal due to the seat vibration. These artifacts could not have been filtered out because the helicopter vibrations represent a whole spectrum of frequencies including harmonics that fall within the main part of a typical EMG power spectrum. Additionally, EMG has usually been analyzed for muscles being maximally and voluntarily contracted, which results in a high EMG voltage. Our experiment attempted to capture the EMG signal from the vibrated individual, who is believed to yield a much

lower level of muscle activity. The resultant signal-to-noise ratio was therefore unacceptable. Figure 38 shows a typical spectrum of EMG compared with seat vibration. It is interesting to note that the vibration spectrum obtained compares well with the work of Laing, Hepler and Merrill (1973) and Shanahan et al (1983).

The impedance transfer function is an acceptable quantity. A typical plot for the average over the nine segments, for one male is shown in Figure 39. However, a detailed analysis of impedance will not be presented for several reasons. The main point of interest in the impedance is the local increase in the magnitude at around 5 Hz, implying a resonant effect.

The rest of the impedance suggests a mostly massive system, since a purely massive system increases linearly with frequency. Since the force transducer was placed under the metal seat frame and not directly under the seated individual, the "system," defined as the individual plus the relatively heavy metal seat frame, is expected to be mostly massive. The only biodynamic effects that emerge are in the 5 Hz region. However, this effect will be seen more clearly and discussed in greater detail for the transmissibility transfer function.

Additionally, a major hypothesis in the study is that there should be consistent changes in the system dynamics, defined by one or more transfer functions, with the onset of fatigue. Since fatigue in general monotonically increased over time, this correlation should be seen as monotonic changes in the transfer functions. It will be shown that this did not occur for transmissibility. Although it will not be presented, this hypothesis also did not hold for impedance.

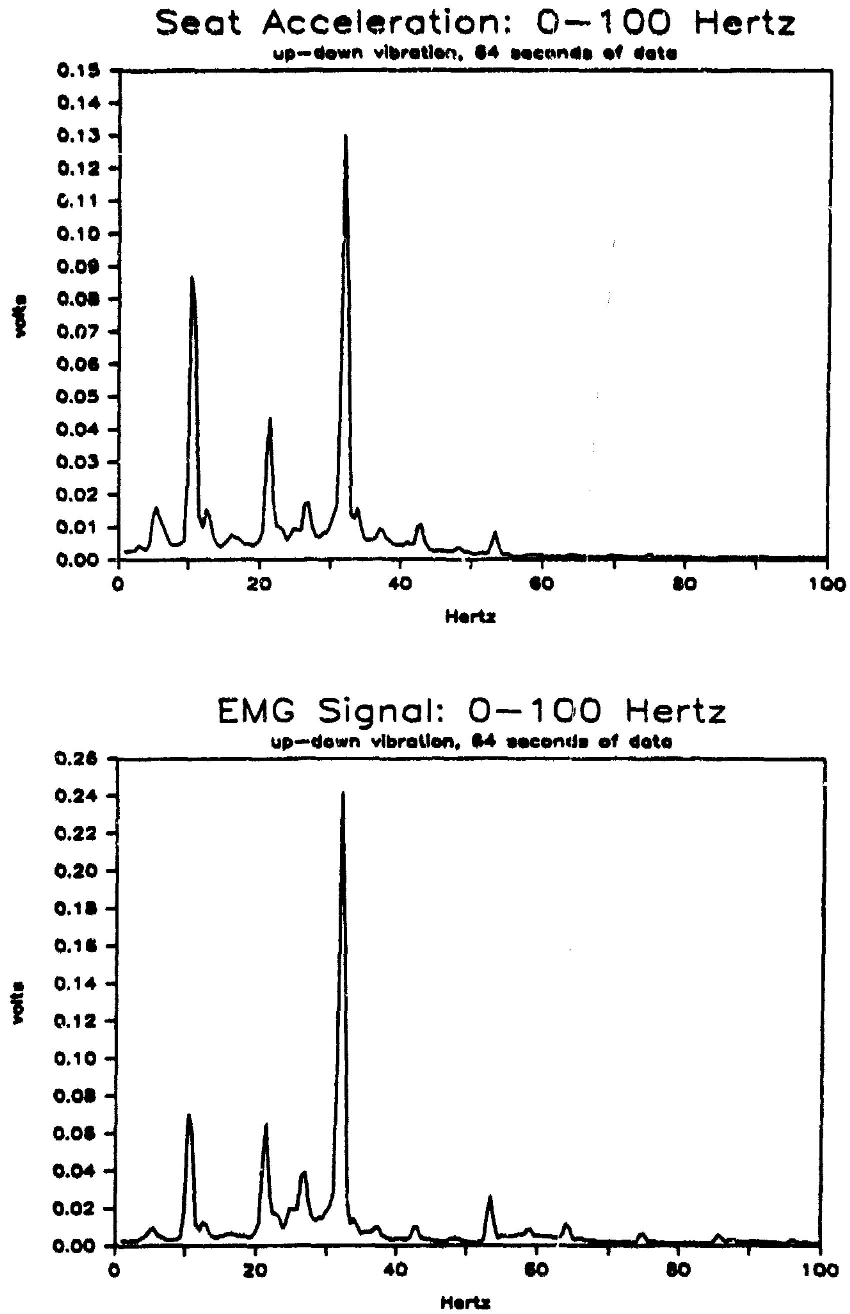
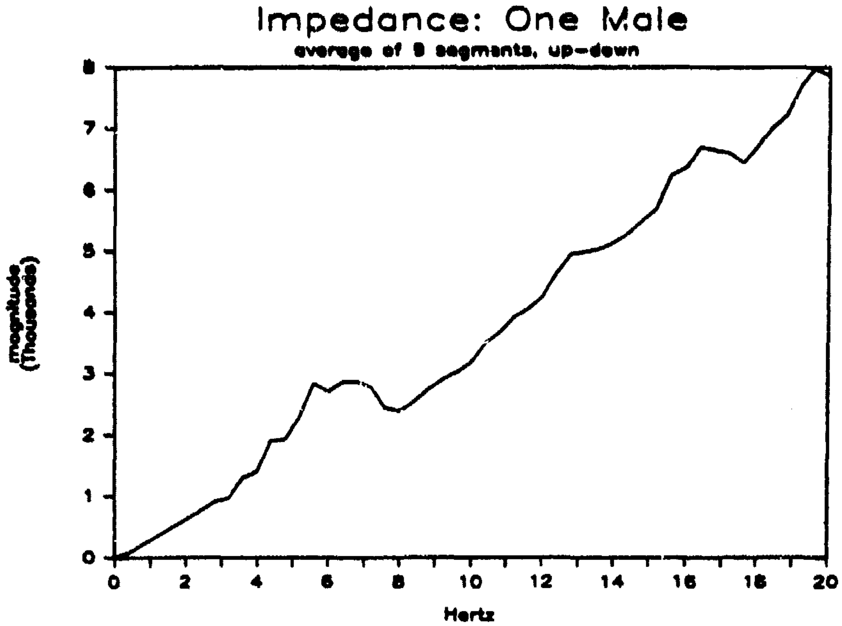


Figure 38. Seat Acceleration and EMG Power Spectra for 0-100 Hz.



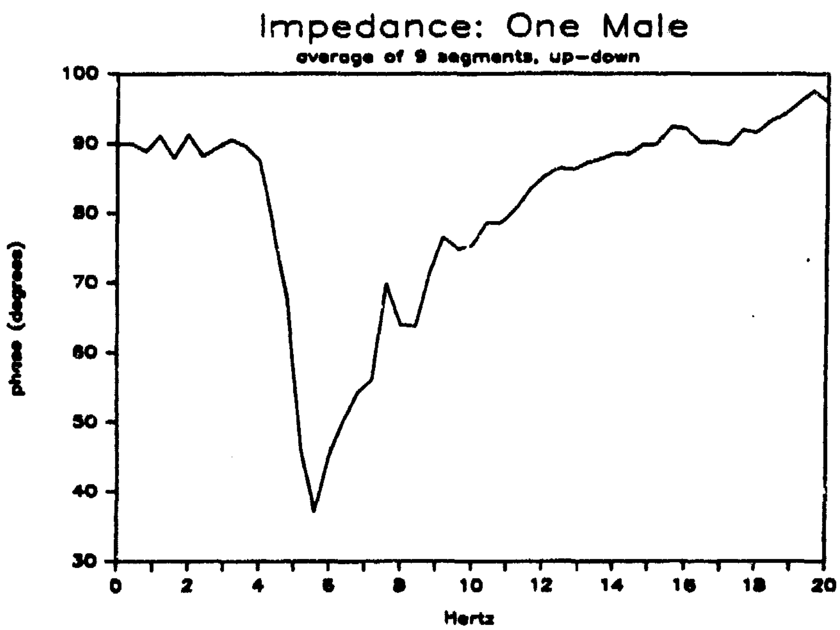


Figure 39. Mechanical Impedance for One Male, 0-20 Hz, Average of Nine Segments.

Finally, the side-to-side mode of vibration was not reduced because the original hypotheses of correlating fatigue to changes in the system dynamics were not found to be true in the up-down and fore-aft vibration modes. Without a clear set of extra physics in the side-to-side vibration mode, it was felt that reducing and analyzing these data was not a fruitful use of resources. Additionally, the average side-to-side vibration is believed to be smaller than the other two modes of vibration.

5.2.3 Valid Data

The major set of data that will be discussed centers around the transmissibility transfer function. There are four sub-groupings of analysis relating to this transfer function: (1) an overview of the data showing the transfer function magnitude and phase, for nine males and nine females over two hours (9 segments), for up-down and fore-aft vibration; (2) the correlation between changes in the transmissibility and increased fatigue over the two hours of vibration (9 segments); (3) the comparison between transmissibility for helicopter up-down vibration versus that for a 20-minute sine sweep from 0-20 Hz; (4) mathematical modeling of the up-down transmissibility, using linear masses, springs and dampers and comparison to experimental data.

5.2.3.1 Overview of Transmissibility

There are transmissibility transfer functions for nine male and nine female subjects, each function having magnitude and phase over

nine segments, in two modes of vibration. The spectrum analyzer computes the transfer function for 0-20 Hz in 0.1 Hz intervals, yielding 200 points per curve. These data (129,600 points) have been reduced in a number of ways. The 0.1 Hz intervals offered by the spectrum analyzer were lumped to 0.4 Hz intervals.

For each mode of vibration, using software written in BASIC, the nine male/female individuals were averaged together at each segment to give what will be called the "generic" male/female. This ninefold reduction in data is also useful because it tends to average out random noise introduced across individuals. A possible drawback of the reduction to the "generic" level is that intersubject variability is obscured. This variability is briefly examined by presenting a sample of data from individual subjects. In addition, the main hypothesis is that individuals show monotonic changes in their transmissibility as a function of increased fatigue. This hypothesis is not obscured at the generic level unless the monotonicity, if it exists, alternates between individuals. This, in fact, does not happen, a further validation of analyzing the data at the generic level.

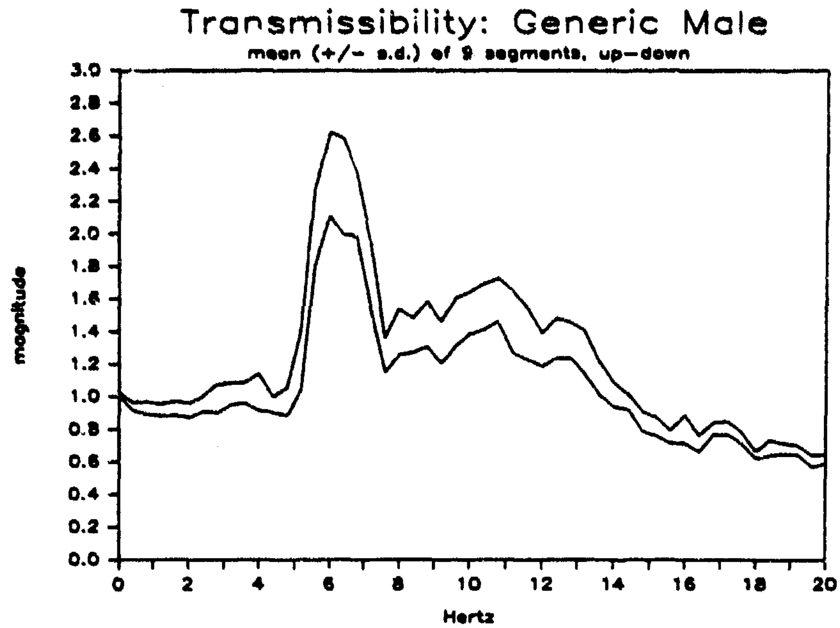
Finally, in parts of the analysis, the data are averaged across frequency intervals or across segments of time. In such instances, the physics behind this procedure is discussed. There is never averaging between the up-down and fore-aft modes of vibration, since their transmissibilities are very unlike each other, suggesting fundamentally different physical systems.

5.2.3.2. Generic Transmissibilities.

The transmissibilities for up-down (UD) vibration for the generic male and female are given in Figures 40 and 41 respectively. The corresponding curves for fore-aft (FA) vibration are shown in Figures 42 and 43. These curves are the mean (plus and minus a standard deviation) of the nine generic transmissibilities which have been generated for each segment of time. They therefore give a measure of the stationarity of the data (Bendat & Piersol, 1980) over the two hours of vibration. A widely banded set of curves suggests that either a physical system is non-stationary over that time period or that a large normalized standard error in the spectrum exists for the given measurement conditions (Barton, 1981).

Since the data are narrowly banded, two conclusions are reached: (1) the physical system is stationary, i.e., its dynamic characteristics are not changing over the two hours of vibration and (2) the variations from 0-20 Hz of the mean spectrum are primarily physical effects, not random fluctuations caused by noise. The first point will suggest little correlation between transmissibility and subjective fatigue, since the latter monotonically increases over the two hours of vibration. In support of the second conclusion, the close similarity between the separately analyzed male and female data sets also suggests systematic changes and not noise.

The UD (Up-Down vibration) transmissibilities in Figures 40 and 41 show a major resonance at around 6 Hz and a smaller, wider second resonance at around 10-12 Hz. The 6 Hz resonance has been found elsewhere in the literature (Dieckman, 1958; Clark et al., 1962; Pradko et al., 1966; Wilder et al., 1982), and agrees with the



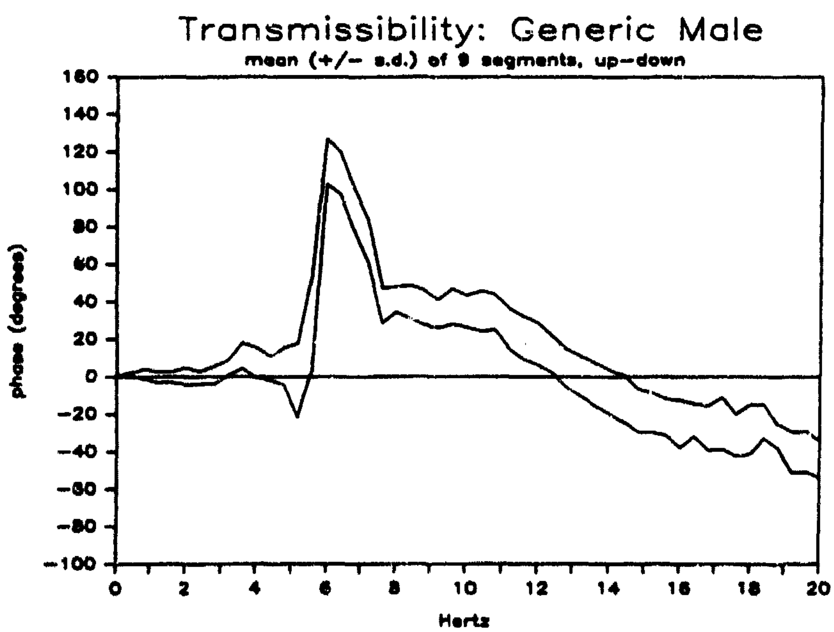


Figure 40. Transmissibility for Generic Male in Up-Down (UD) Vibration: Average of Nine Segments.

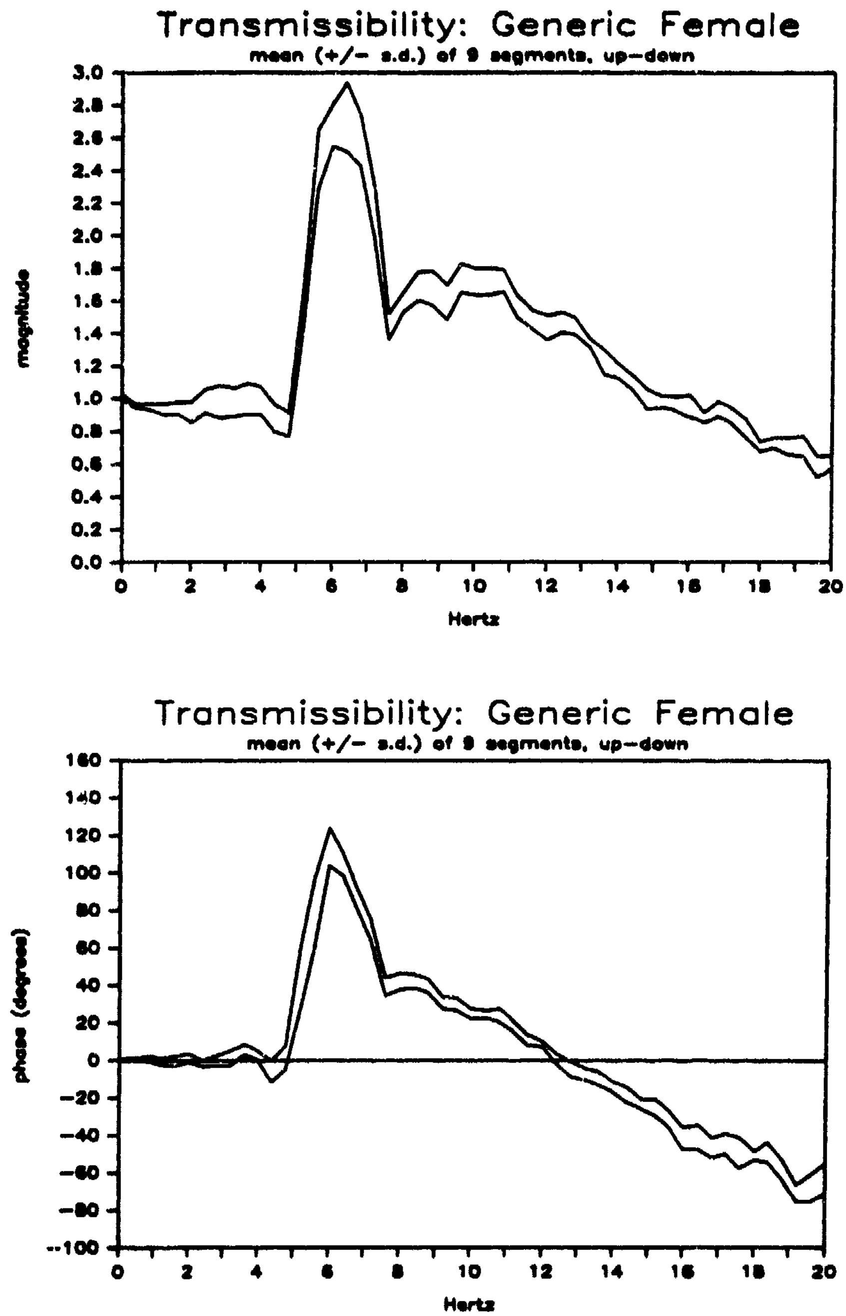
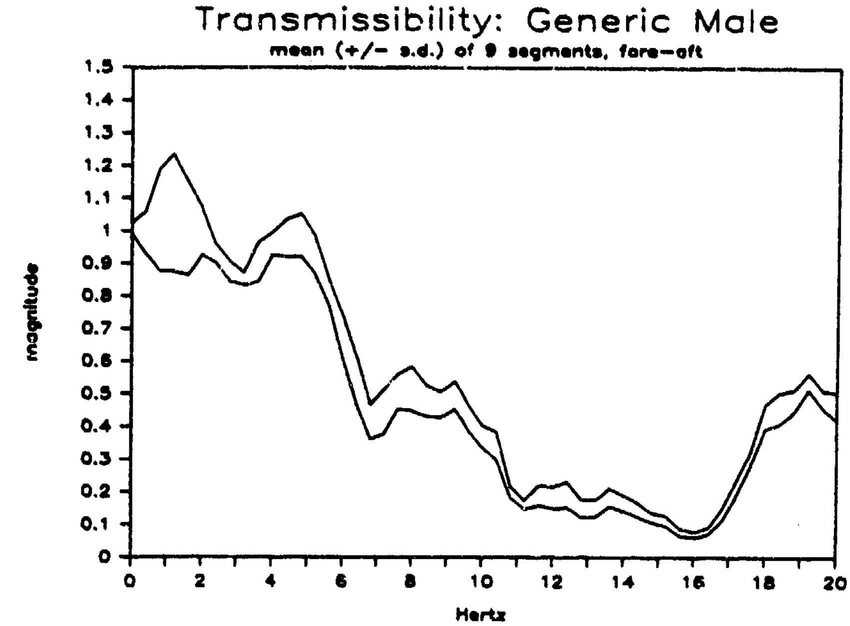


Figure 41. Transmissibility for Generic Female in Up-Down (UD) Vibration: Average of Nine Segments.



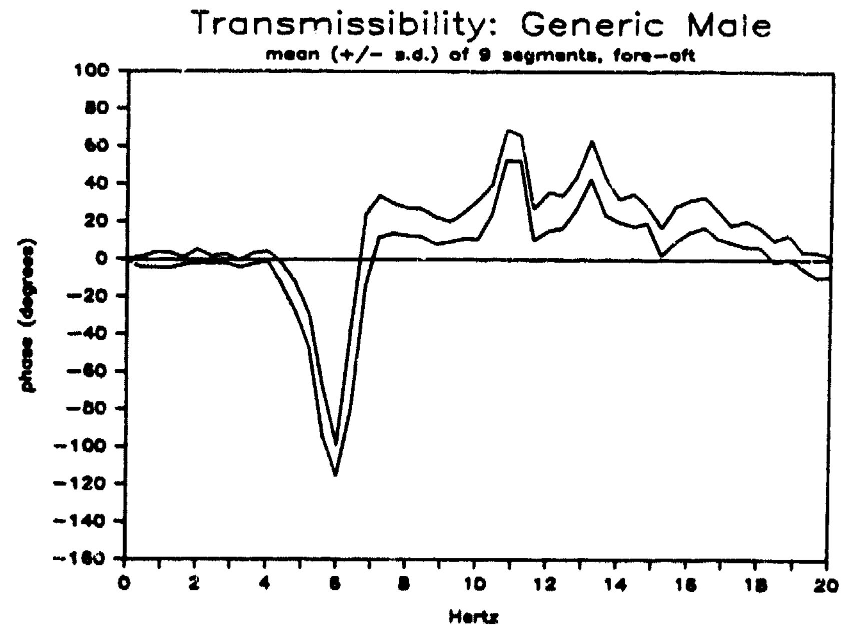


Figure 42. Transmissibility for Generic Male in Fore-Aft (FA) Vibration: Average of Nine Segments.

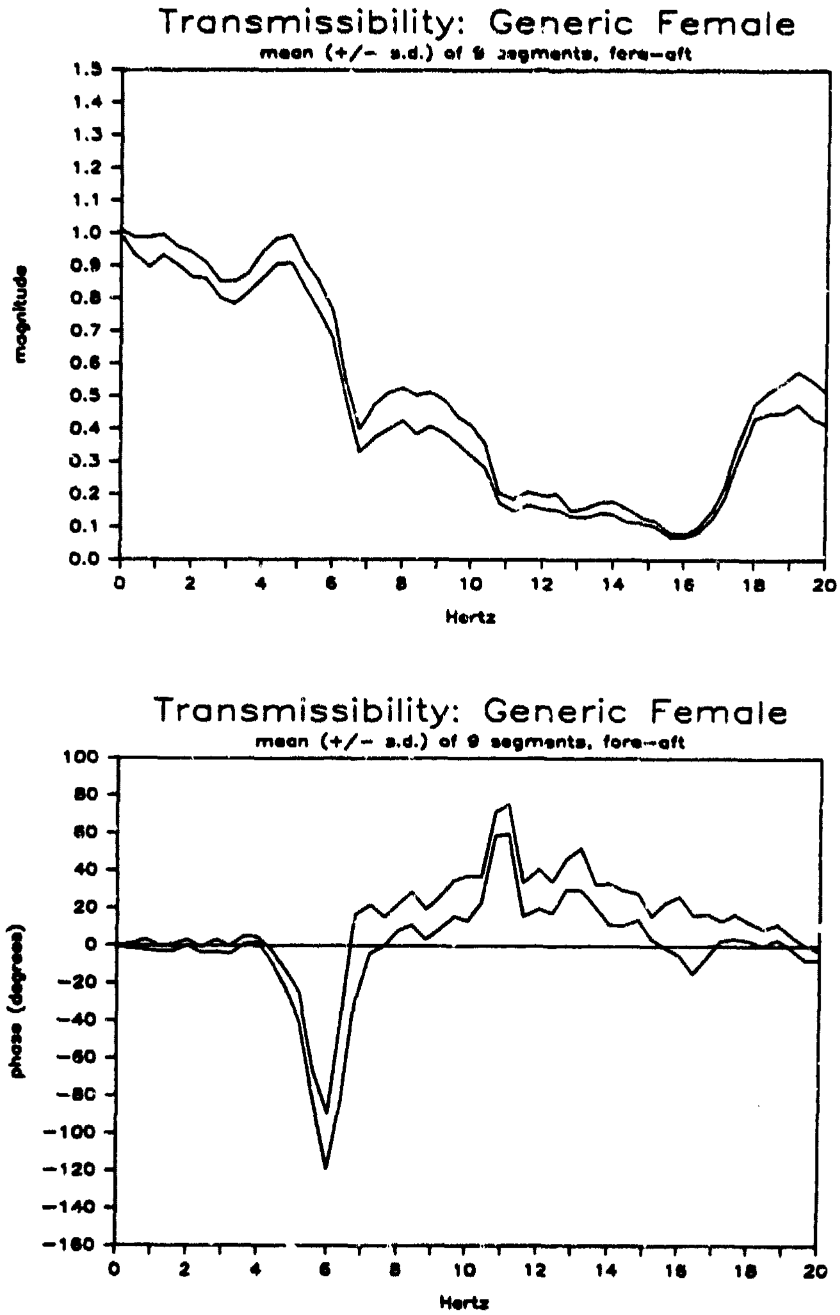


Figure 43. Transmissibility for Generic Female in Fore-Aft (FA) Vibration: Average of Nine Segments.

ISO-2631 (ISO, 1978) standard for human sensitivity to whole body vibration.

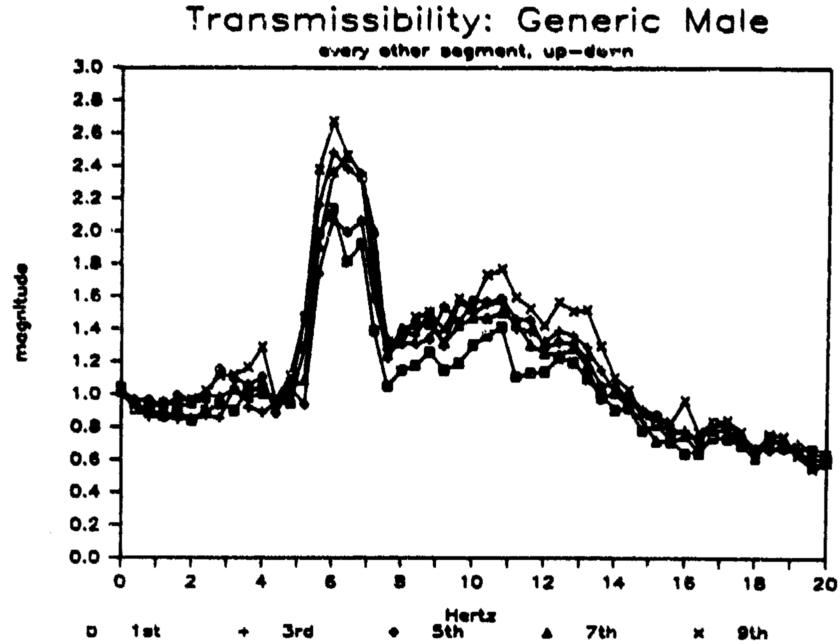
The FA (Fore-Aft vibration) transmissibilities in Figures 42 and 43 are markedly different. The average magnitude is somewhat lower than that for UD vibration. If a resonance can be defined here, it is in the region of 0-4 Hz, which again agrees with the ISO standard for FA vibration. One might speculate that the lower resonance for FA versus UD vibration (0-4 Hz versus 6 Hz) comes from an effectively smaller upper body stiffness due to greater trunk mobility in the FA direction.

The curves in Figures 40 through 43 also suggest that the female data are more narrowly banded than the male data. A possible cause is the greater variance in the physical dimensions of males versus females.

5.2.3.3 Correlation of Transmissibility to Subjective Findings.

Variations in transmissibility from one segment in time to the next was generally random. However, subjective fatigue, as measured by the visual analog scale (VAS) increased monotonically. The conclusion is that transmissibility does not correlate with subjective fatigue. In fact, the data presented in the last section suggest that transmissibility does not change significantly over the two-hour exposure to vibration.

Graphs of UD transmissibility for the generic male and female for the first, third, fifth, seventh and ninth segments are shown in Figures 44 and 45. These curves show that generally no monotonic trends occur from one segment to the next. This was also true for



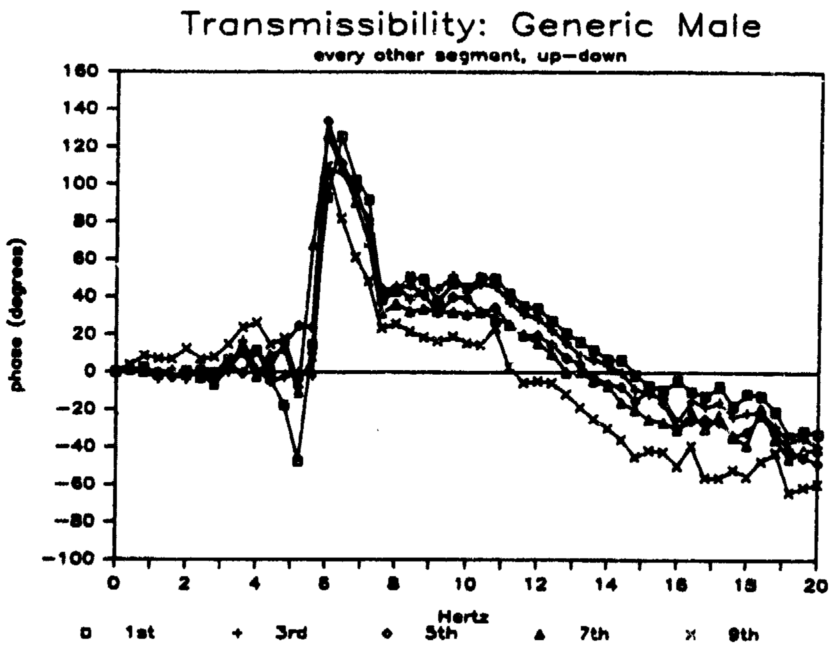


Figure 44. Transmissibility for Generic Male in UD Vibration: 1st, 3rd, 5th, 7th and 9th Segments.

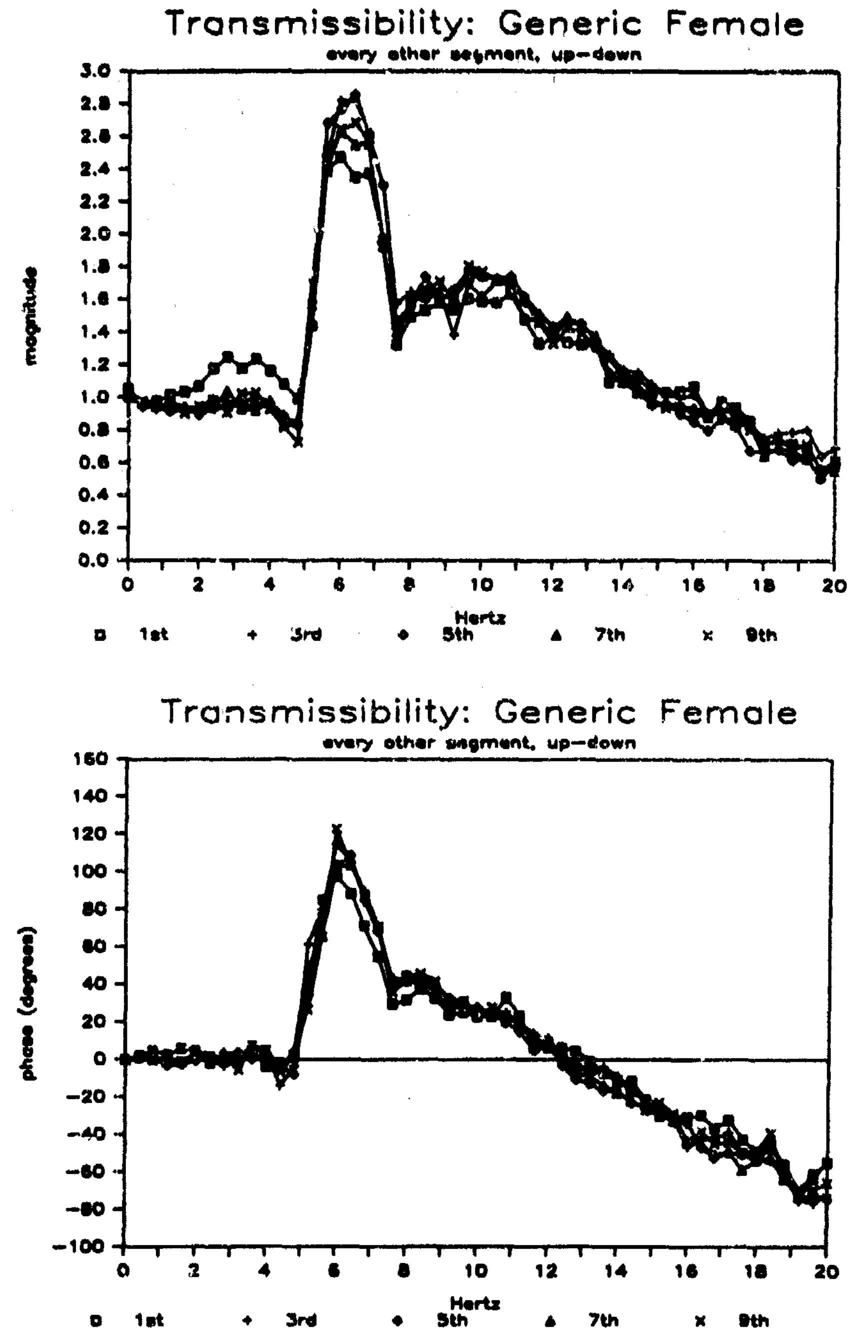


Figure 45. Transmissibility for Generic Female in UD Vibration: 1st, 3rd, 5th, 7th and 9th Segments.

the FA mode of vibration. The UD generic male data do suggest a significant change from the first to the ninth segment, but neither the intermediate segments, nor the female-UD, male-FA, or female-FA data followed this pattern. These curves again support the conclusion that, within expected experimental error, the generic male/female UD/FA physical systems are described as stationary, in the language of random data analysis.

To ensure that pre-averaging individual subjects to the generic level does not average out possible trends across segments, UD and FA transmissibility data for individual males and females are plotted in Figures 46 through 49. These figures show the average transmissibility magnitude within a 4 Hz region of the 0-20 Hz spectrum. In order to capture resonant effects, this region is from 4-8 Hz for UD vibration and from 0-4 Hz for FA vibration. However, it has been found that the average over the 20 Hz spectrum divided by the average within this 4 Hz band (e.g., for females in UD vibration: mean = .73, S.D. = .13) is a fairly constant ratio which helps validate using a single number to represent the average behavior of the entire curve. These figures again show either no monotonic trends or, as in the case of females for FA vibration, hardly any variation at all. It is therefore believed that changes across segments, at either the generic or individual level, are associated with statistical uncertainty and not physical changes in whole body vibration.

A final way of illustrating the lack of correlation between changes in transmissibility and subjective fatigue across segments is shown in Figures 50 through 53. Here, the average transmissibility

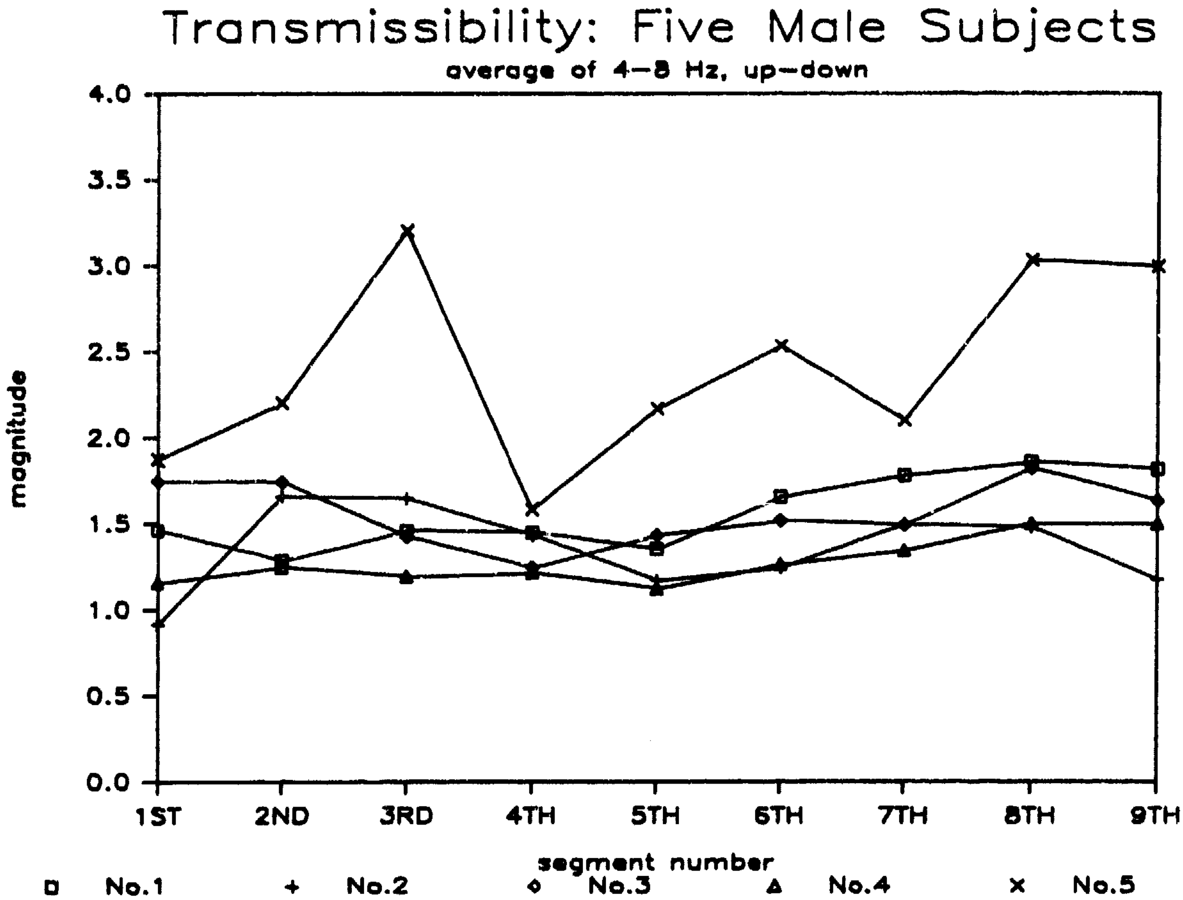


Figure 46. Transmissibility for Five Male Subjects in UD Vibration: Average Magnitude from 4-8 Hz for Each Segment.

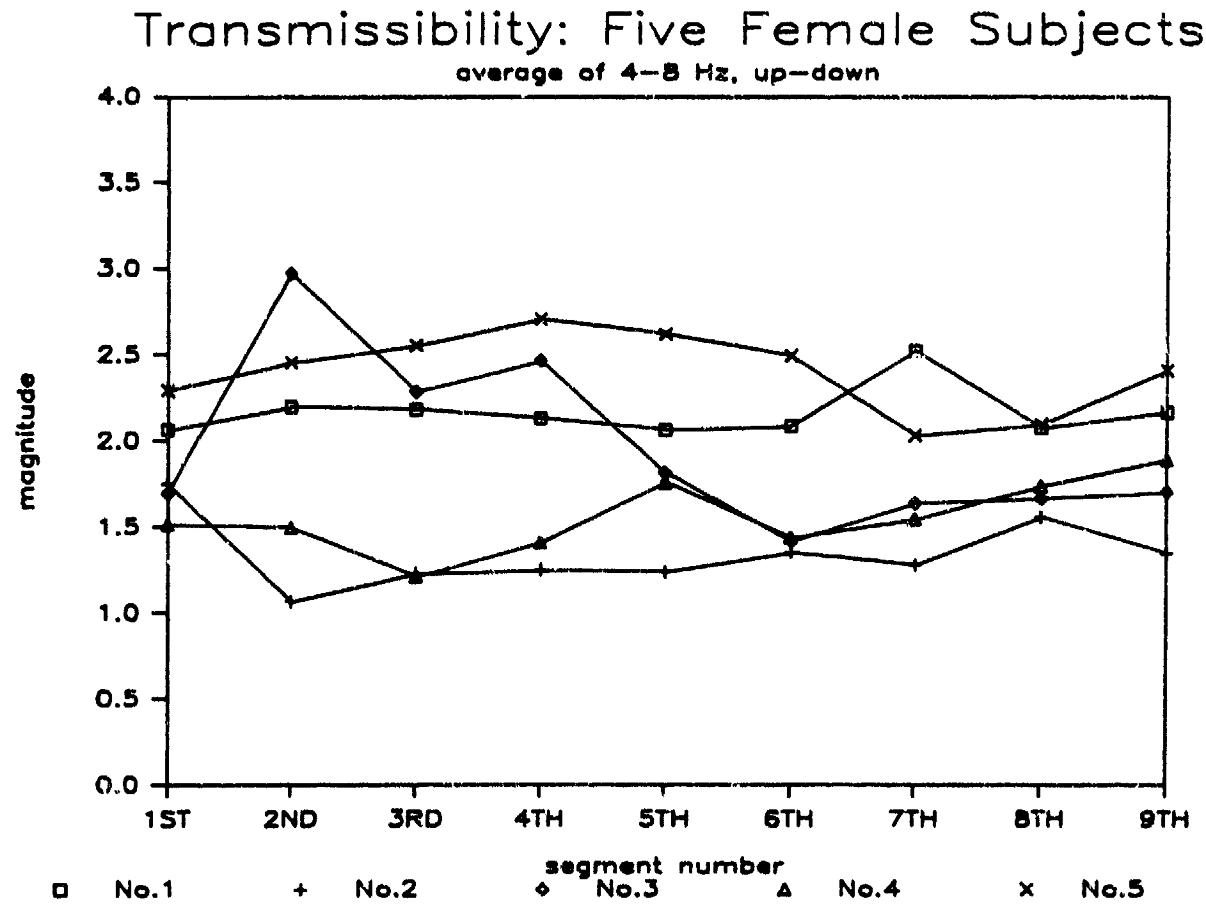


Figure 47. Transmissibility for Five Female Subjects in UD Vibration: Average Magnitude from 4-8 Hz for Each Segment.

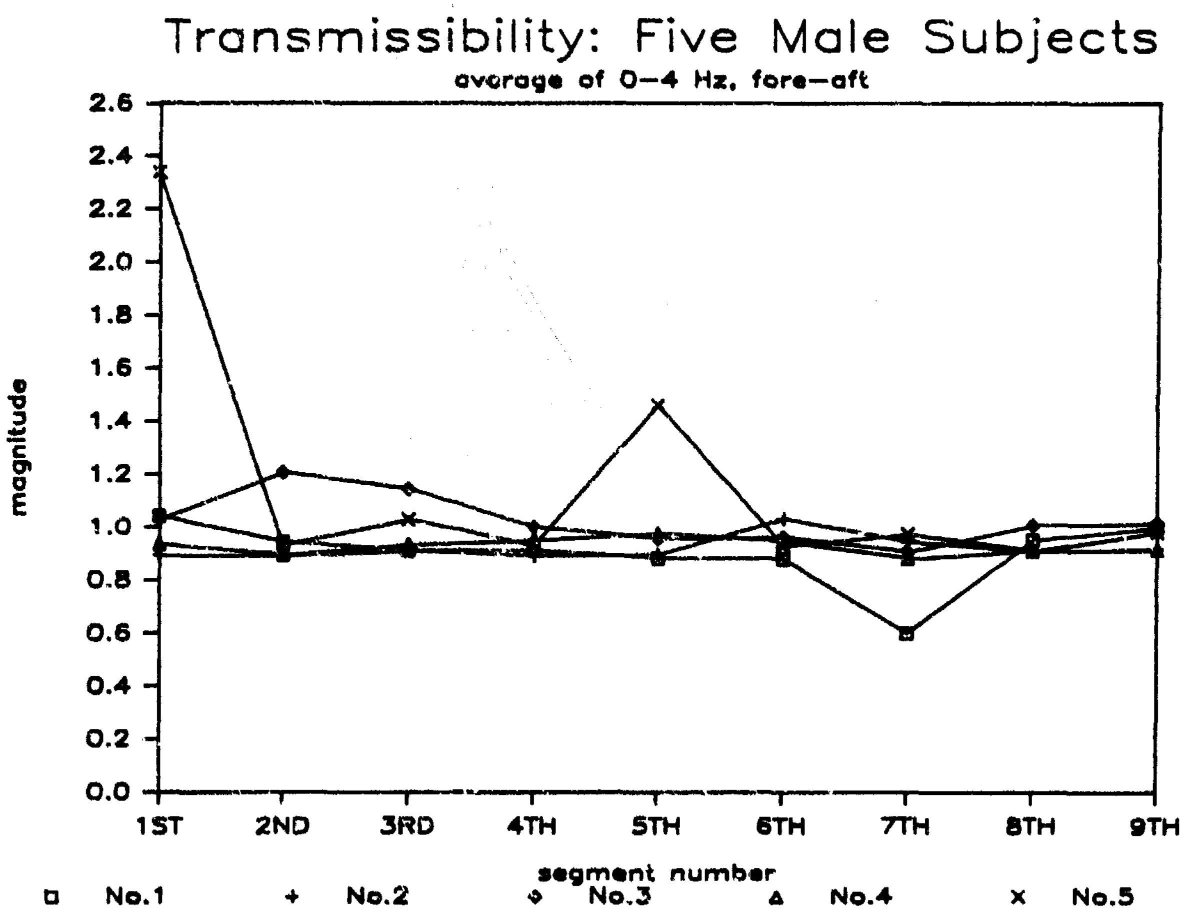


Figure 48. Transmissibility for Five Male Subjects in FA Vibration: Average Magnitude from 0-4 Hz for Each Segment.

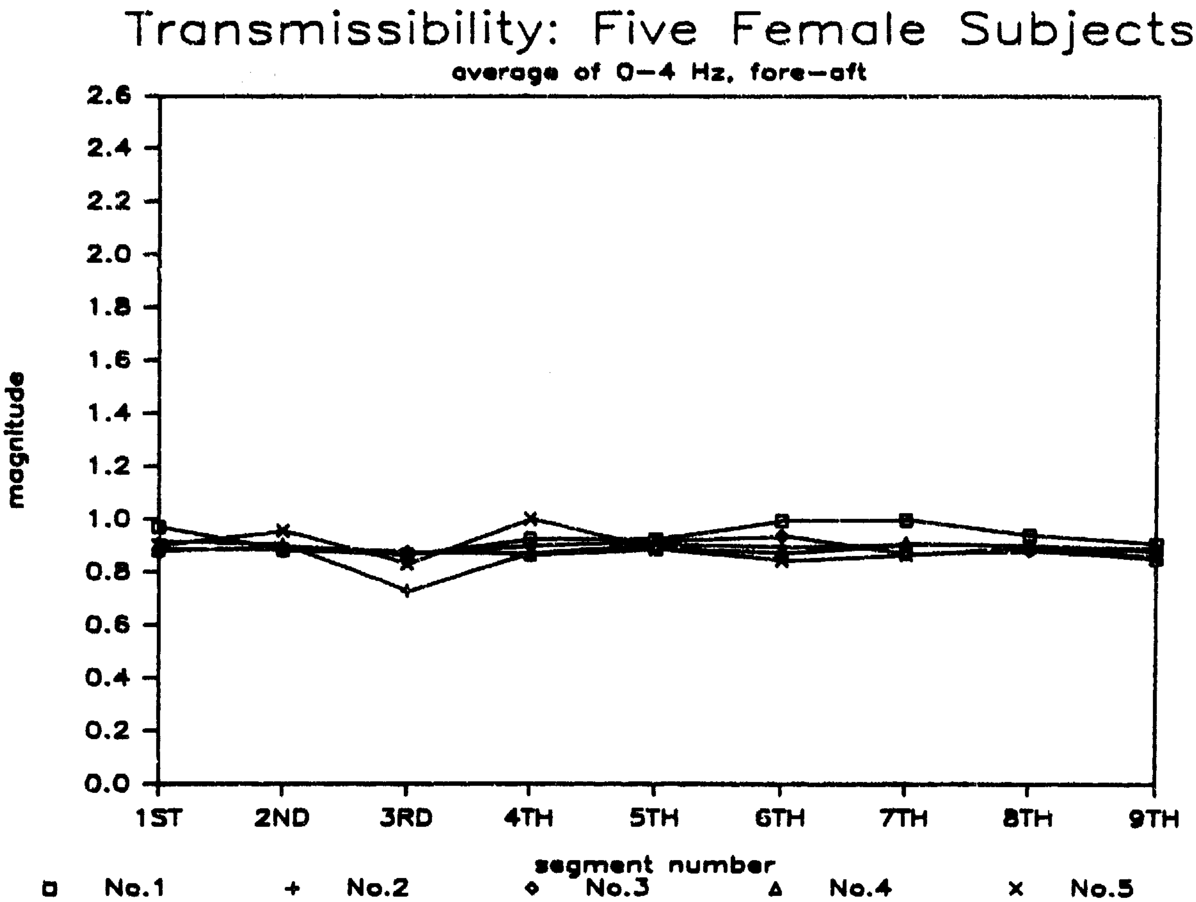


Figure 49. Transmissibility for Five Female Subjects in FA Vibration: Average Magnitude from 0-4 Hz for Each Segment.

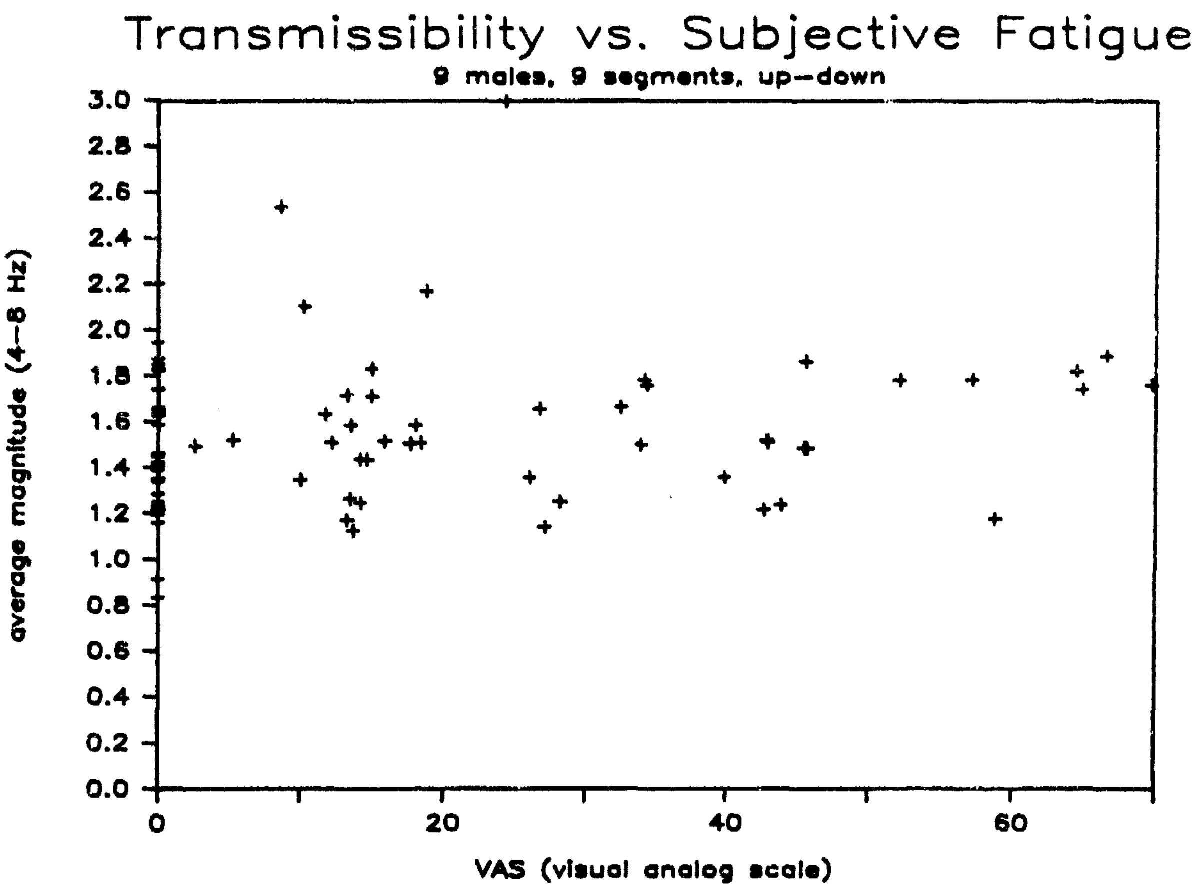


Figure 50. Transmissibility versus Subjective Fatigue: Nine Males in UD Vibration.

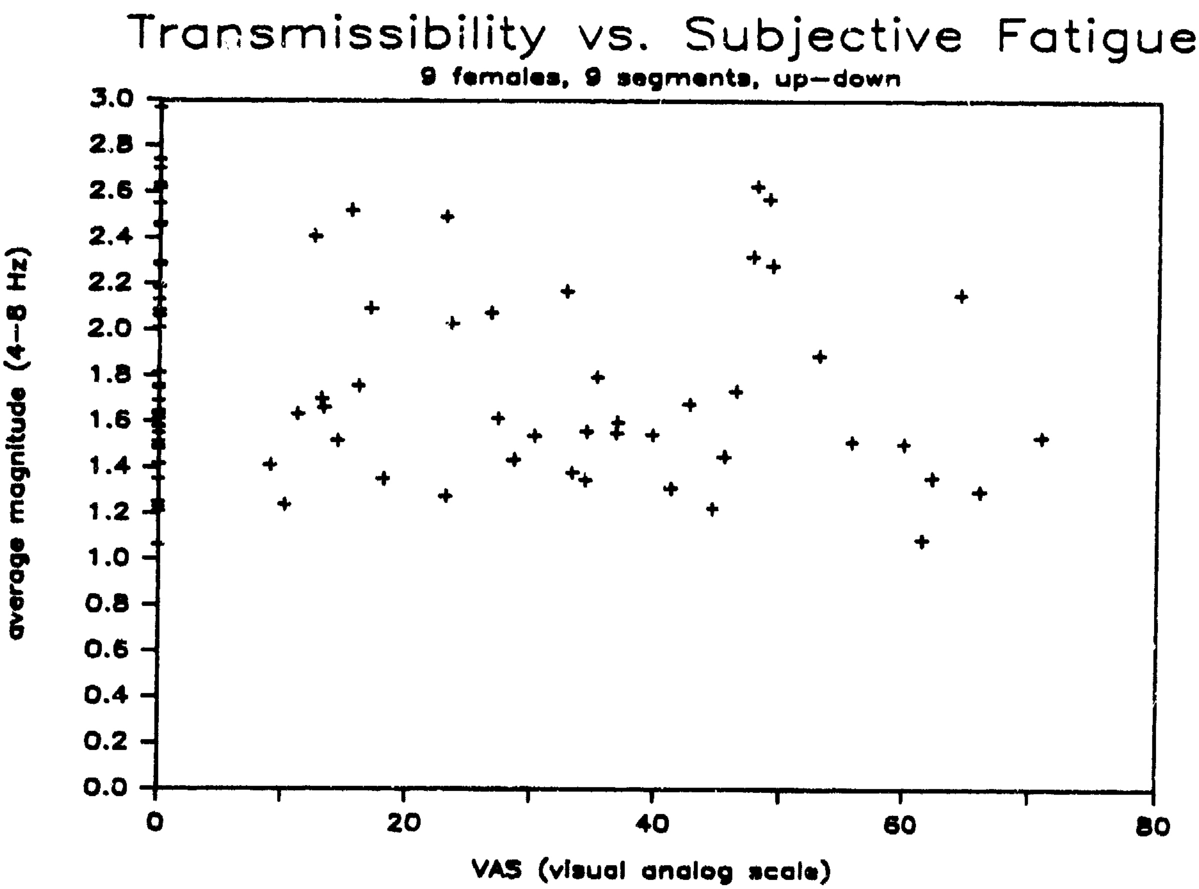


Figure 51. Transmissibility versus Subjective Fatigue: Nine Females in UD Vibration.

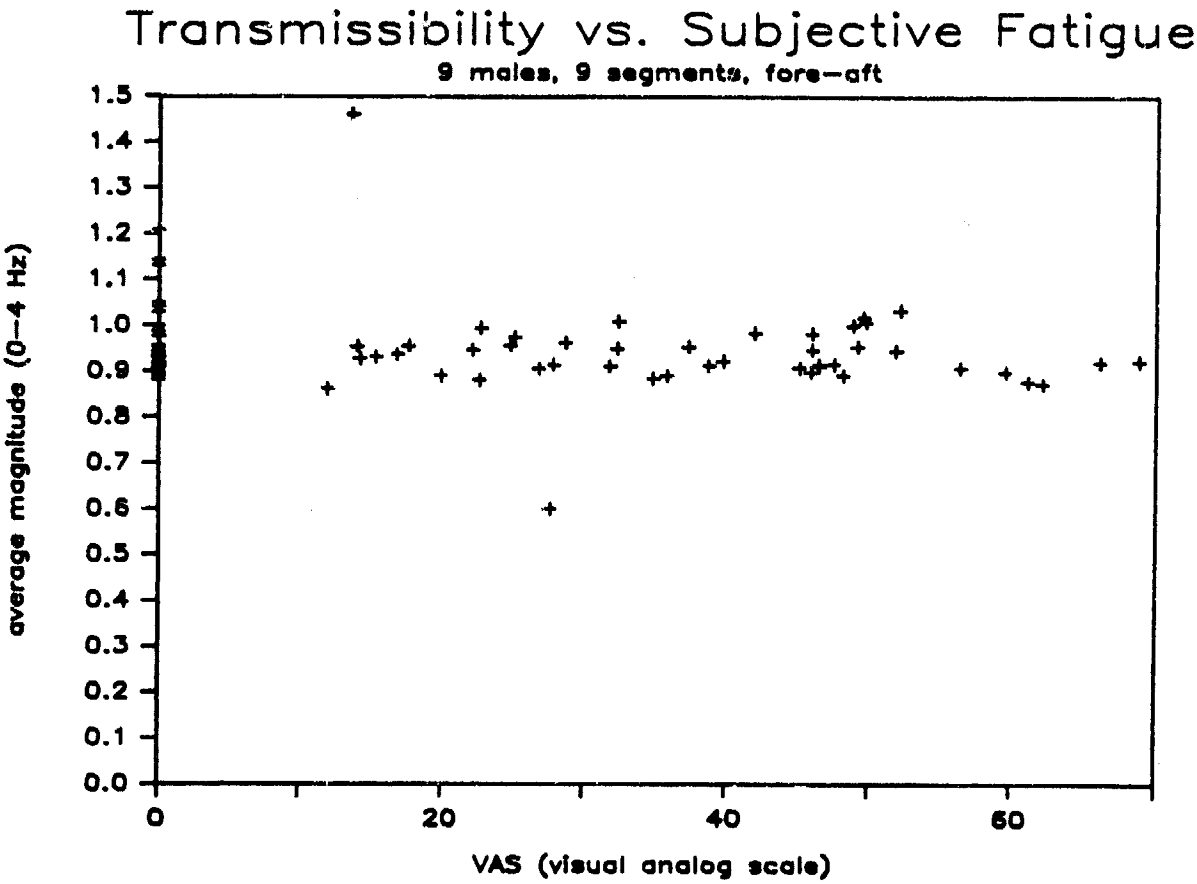


Figure 52. Transmissibility versus Subjective Fatigue: Nine Males in FA Vibration.

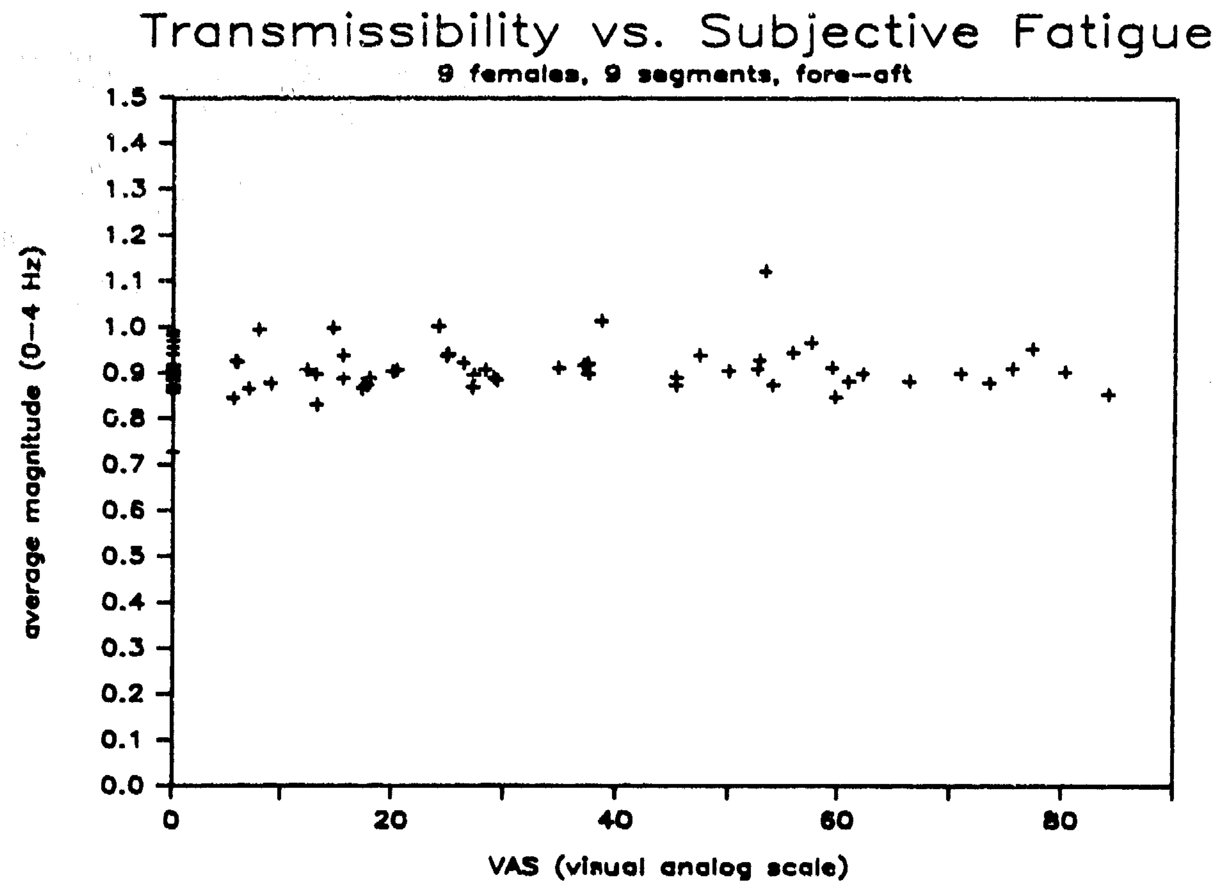


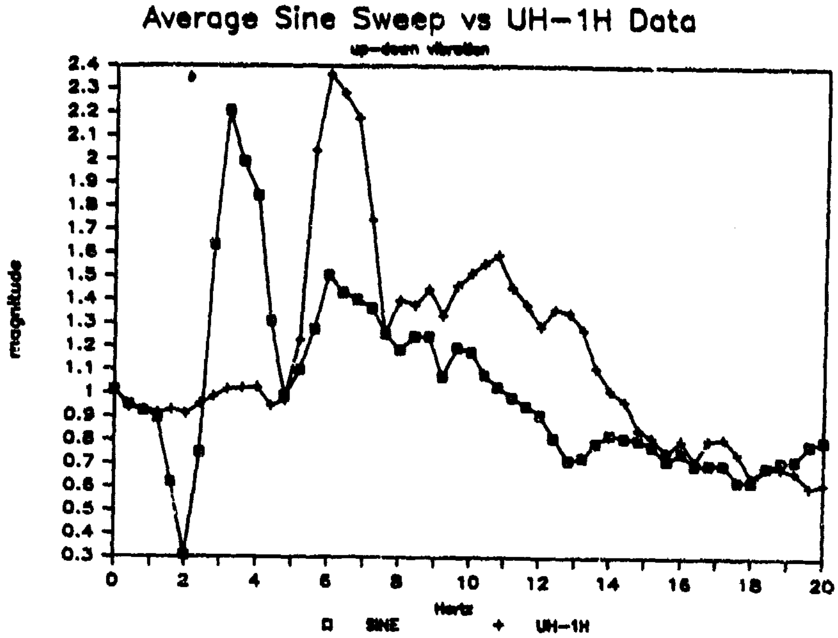
Figure 53. Transmissibility versus Subjective Fatigue: Nine Females in FA Vibration.

magnitudes over the previously defined 4 Hz region in UD (4-8 Hz) and FA (0-4 Hz) vibration are plotted against readings on the visual analog scale (VAS) for all individuals for all nine segments. No regression analysis was performed because of the obvious lack of correlation shown in these data.

5.2.3.4 Relationship Between Helicopter and Sine-Sweep Data.

As a means of characterizing the simulated helicopter seat, five male subjects were subjected to a 20-minute sine sweep of UD vibration over 0-20 Hz. Their transmissibilities were averaged at each frequency interval and compared with the average transmissibility (for the first segment) of the nine males subjected to UD helicopter vibration. The latter is the previously defined "generic" transmissibility. This comparison is crude because the five sine-swept males were different from the nine males subjected to helicopter vibrations. However, assuming a similar vibration response across individuals, transmissibility as a transfer function must be the same in both kinds of vibration if the human body/seat frame system is linear. Figure 54 shows this comparison, the curve labeled "UH-1H" representing the helicopter vibrations. The two curves are similar in shape but resonate at different frequencies with peaks at roughly 3.2 Hz and 6 Hz for the sine sweep and helicopter vibration respectively. The sine sweep transmissibility phase oscillates wildly at 15-20 Hz, but this is believed to be an instrumentation error, since it occurs for only one out of the five individuals.

If the "UH-1H" curves are shifted back by 2.8 Hz, then the similarity becomes striking. This is shown in Figure 55. The



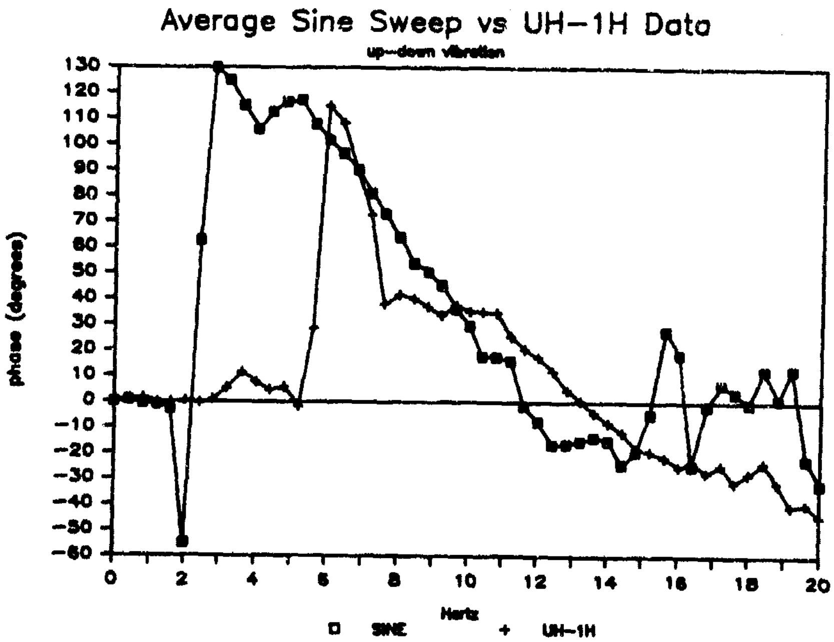
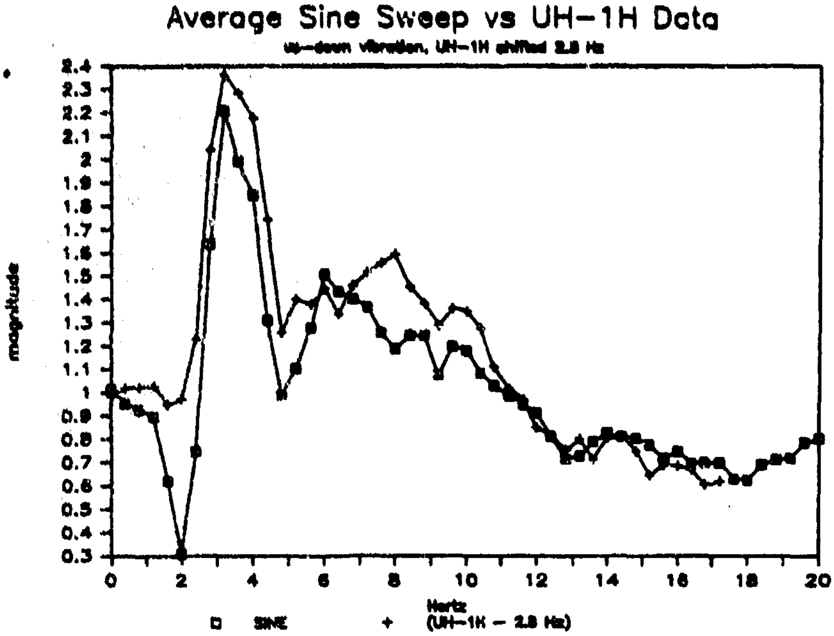


Figure 54. Average Sine Sweep versus UH-1H Data: UD Vibration.



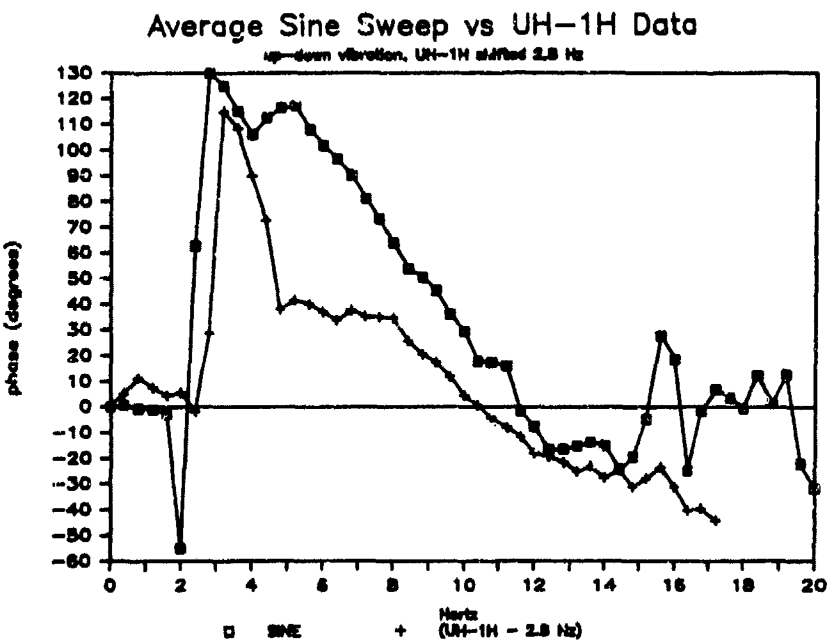


Figure 55. Average Sine Sweep versus UH-1H Data: UD Vibration, UH-1H Data Shifted 2.8 Hz.

magnitude curves track each other for almost the entire spectrum. Considering that these data represent averages of two sets of males whose individual transmissibilities vary widely, the results are encouraging. The 2.8 Hz shift remains unexplained. It is not believed to be a measure of the non-linearity of the system, since this would more likely show up as harmonics, rather than a simple frequency shift. Instrumentation was the same in both cases, although the spectrum analyzer may somehow preferentially weight the lower frequencies during the 20-minute processing of the sine sweep data.

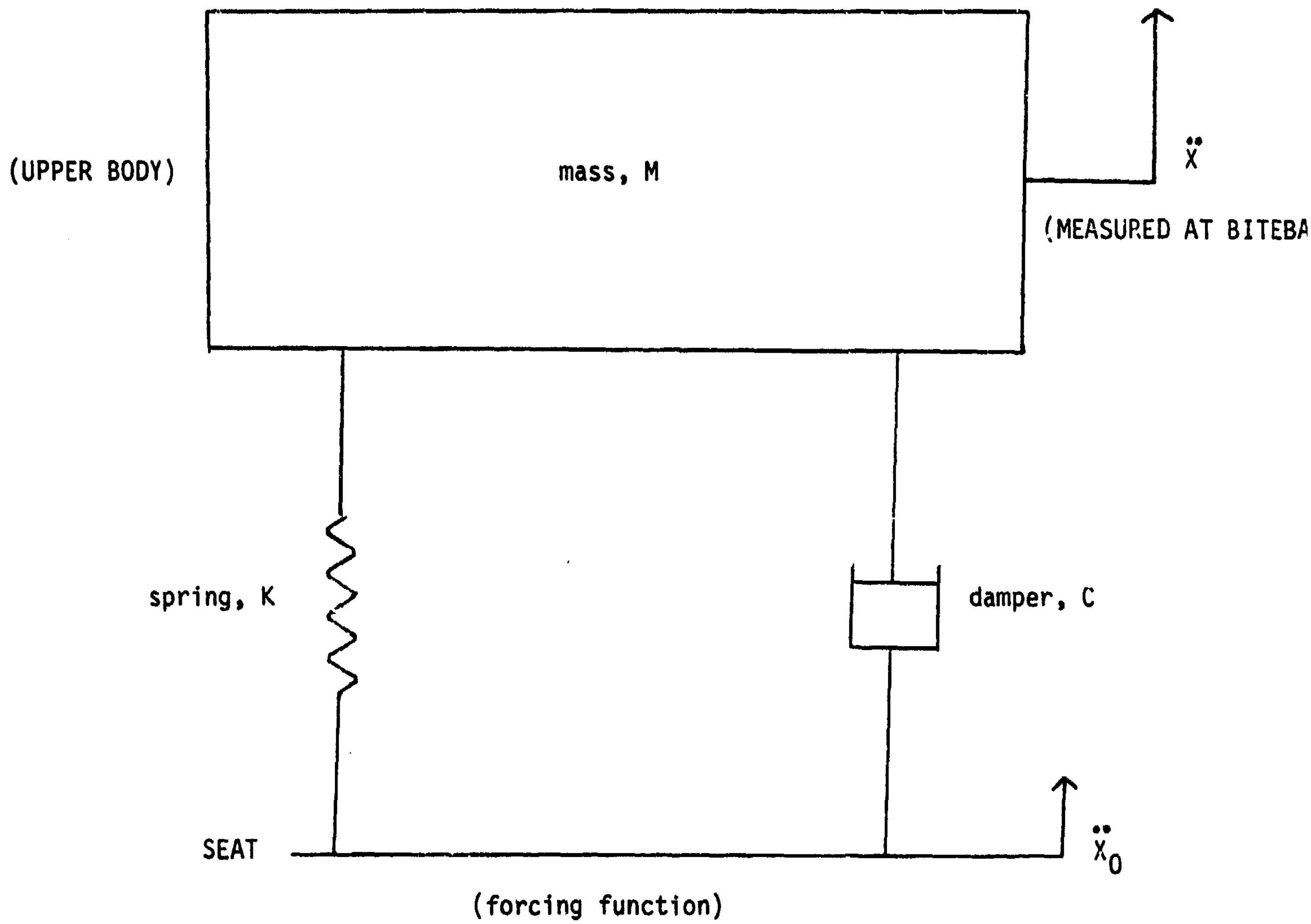
5.2.3.5 Mathematical Modeling of Up-Down Transmissibility as a Linear System.

The single prominent resonance at 6 Hz of the UD transmissibility curves in Figures 40 and 41 suggest a simple mechanical system with few vibrational degrees of freedom. By modeling the whole body vibration data as a physical system of masses, springs and dampers, one can attach variations in the data to equivalent parametric changes in the physical system. The most simple modeling approach, and the one used here, assumes linear mass-spring-damper networks. The good correlation of the helicopter vibration data to sine sweep data found in Section 5.2.3.4 helps justify this assumption.

Two models are explored for whole body vibration. The first is a one degree-of-freedom (1-DOF) mass-spring-damper network commonly used in the theory of vibrations (Seto, 1964). The second cascades two 1-DOF networks, one with a parallel spring-damper and the other with a serial spring-damper, to form a 2-DOF system.

The 1-DOF system structure is shown in Figure 56. It is made up of a mass (M) connected in series to a spring (K) and damper (C) pair in parallel. Since the components of the system are assumed to be linear, the transfer function (X/X_0) can be solved analytically using Laplace transforms.

The existence of both a mass and a spring allows for a single resonance to occur which is needed for fitting the 6 Hz resonance of the experimental data. This fit to experimental data is achieved visually by changing the parameters K/M and C/M, and is shown in



TRANSMISSIBILITY (seat-to-bitebar) is $\ddot{X}/\ddot{X}_0$

Figure 56. Whole Body Vibration as a 1-DOF Linear Mass-Spring-Damper System.

Figure 57 for the magnitude and phase of the transmissibility. The mean generic male UD transmissibility is used for this figure. Note that no optimized curve-fitting procedure has been used here since only a qualitative understanding of the physical system structure is being sought. However, for the values of K/M (1575 sec^{-2}) and C/M (17.5 sec^{-2}) chosen for Figure 57, the damping ratio is approximately .22, which is near values cited elsewhere in the literature (Payne and Band, 1971).

The motivation for the second more complex model (2-DOF) is to allow for a second resonance besides the prominent resonance at around 6 Hz. The 2-DOF system structure is shown in Figure 58. The upper network is a serially connected mass-spring-damper; the lower network is as before.

The upper network structure has been chosen for its ability to match experimental data, and not as an appeal to the physics of whole body vibration. It can be seen that merely cascading two 1-DOF networks of the original structure will not provide a good experimental fit because the transmissibility phase at high frequencies will be much larger for the theoretical versus experimental data. The entirely serial upper network pulls the phase down at large frequencies, counteracting the contribution from the lower network.

There is a concern that the serial upper network allows infinite movement for a static finite force, like putting a weight on an infinitely long bicycle pump. A refinement to the proposed model to prevent this unphysical defect is either a mechanical stop limiting the physical motion (e.g. the facets in the spine) or the stipulation that

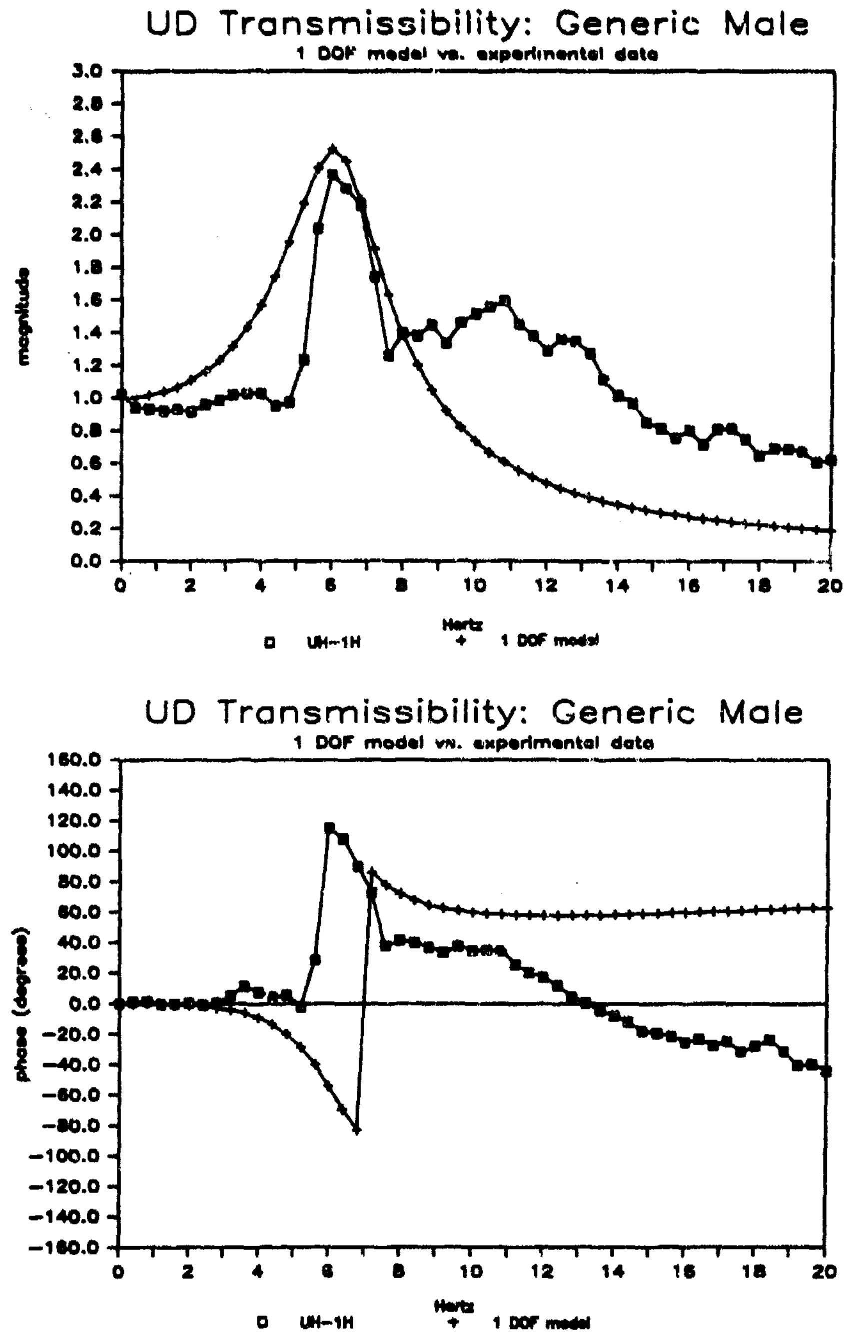
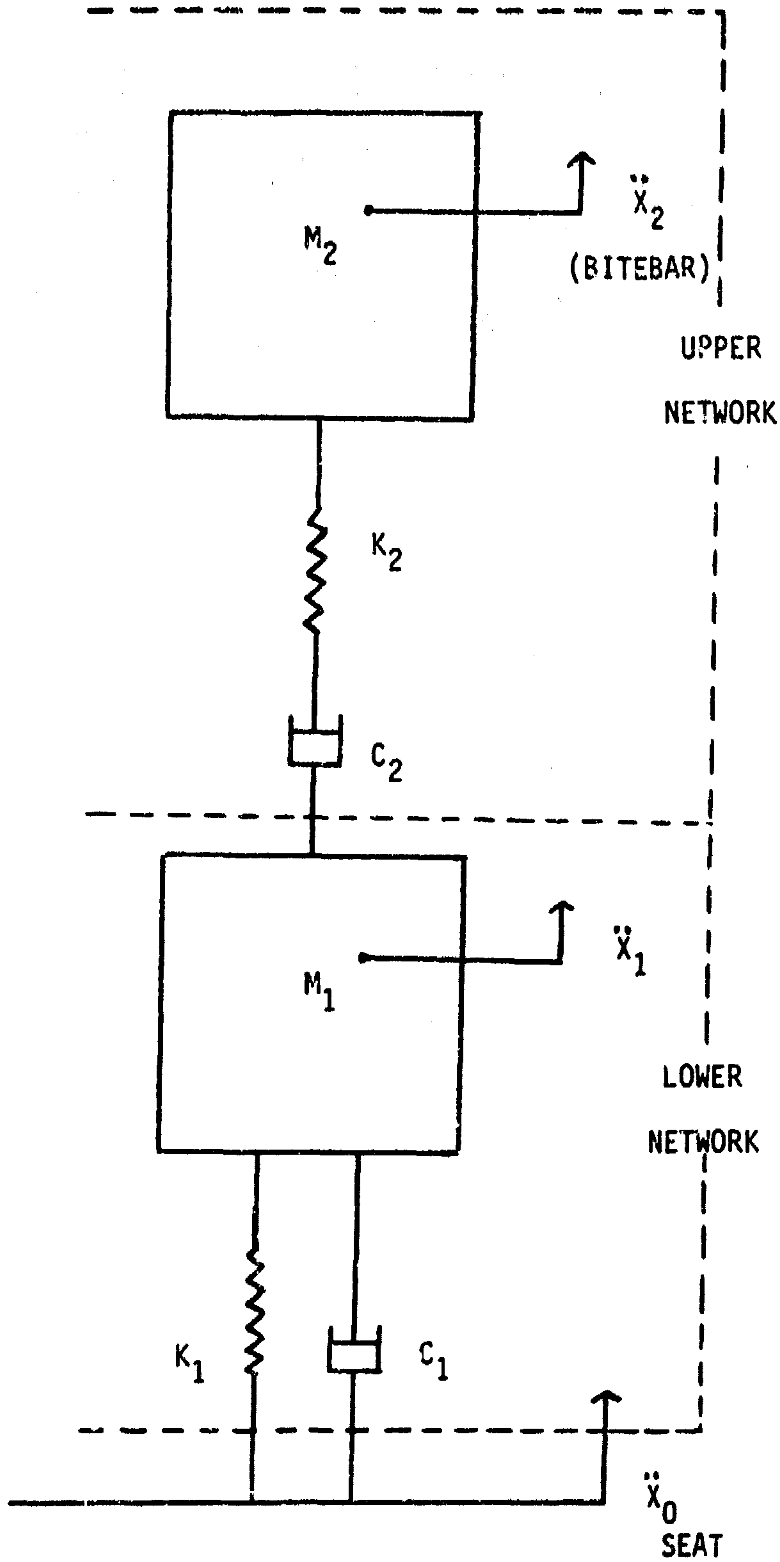


Figure 57. 1-DOF Model versus Experimental Data: UD Vibration.



OVERALL TRANSMISSIBILITY (seat-to-bitebar): $\ddot{X}_2/\ddot{X}_0 = (\ddot{X}_2/\ddot{X}_1)\cdot(\ddot{X}_1/\ddot{X}_0)$

Figure 58. Whole Body Vibration as a 2-DOF Linear System.

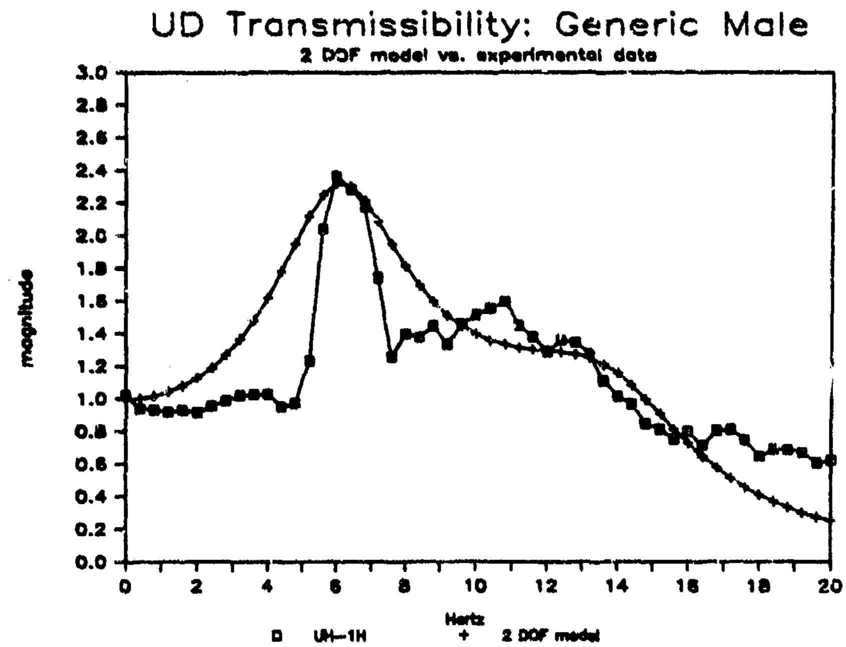
this model works for loads that are zero when integrated over time ("A.C." loads only).

The fit between the 2-DOF model and the experimental data is shown in Figure 59 for the transmissibility magnitude and phase. For the magnitude, the 2-DOF model displays a second resonance at around 12-14 Hz and is therefore arguably closer to the experimental data, although again no formal curve-fitting procedure has been employed. The phase does not compare as well at lower frequencies, but at larger frequencies the model and the experimental data are now matched closely. The upper network K/M and C/M are 8100 sec^{-2} and 35 sec^{-1} respectively. The corresponding values for the lower network are 1575 sec^{-2} and 25 sec^{-1}. These yield damping ratios of .19 and .31 for the upper and lower networks respectively.

5.3 Fatigue Assessment Using Change in the Back Surface Motion Behavior in a Vertical Vibration Environment

Motion of each point located in the cluster of points across the back (over the scapulae) was plotted against its mean initial location along the side-to-side axis (lateral). Motion of each point located along the spine (over the spinous processes) was plotted against its mean initial height along the vertical axis. Individual cases are indicated in Figures 60 through 86. Averages with linear regression lines and r^2 (correlation coefficient squared) values are found in Figures 87 through 92.

Changes did occur in the amount each point across the back could move, resulting from exposure to UH-1H seated vertical vibration. Shifts upward in the regression lines for the fore-aft and



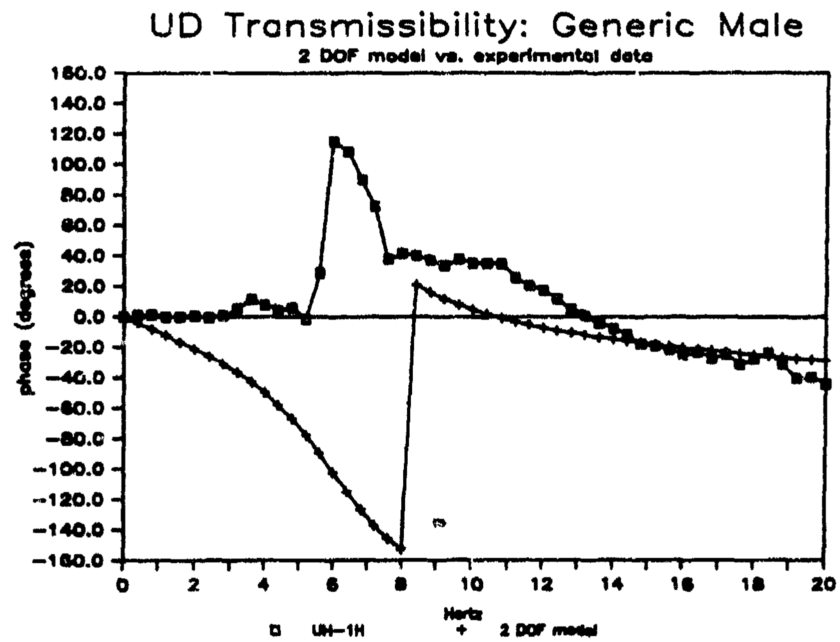


Figure 59. 2-DOF Model versus Experimental Data: UD Vibration.

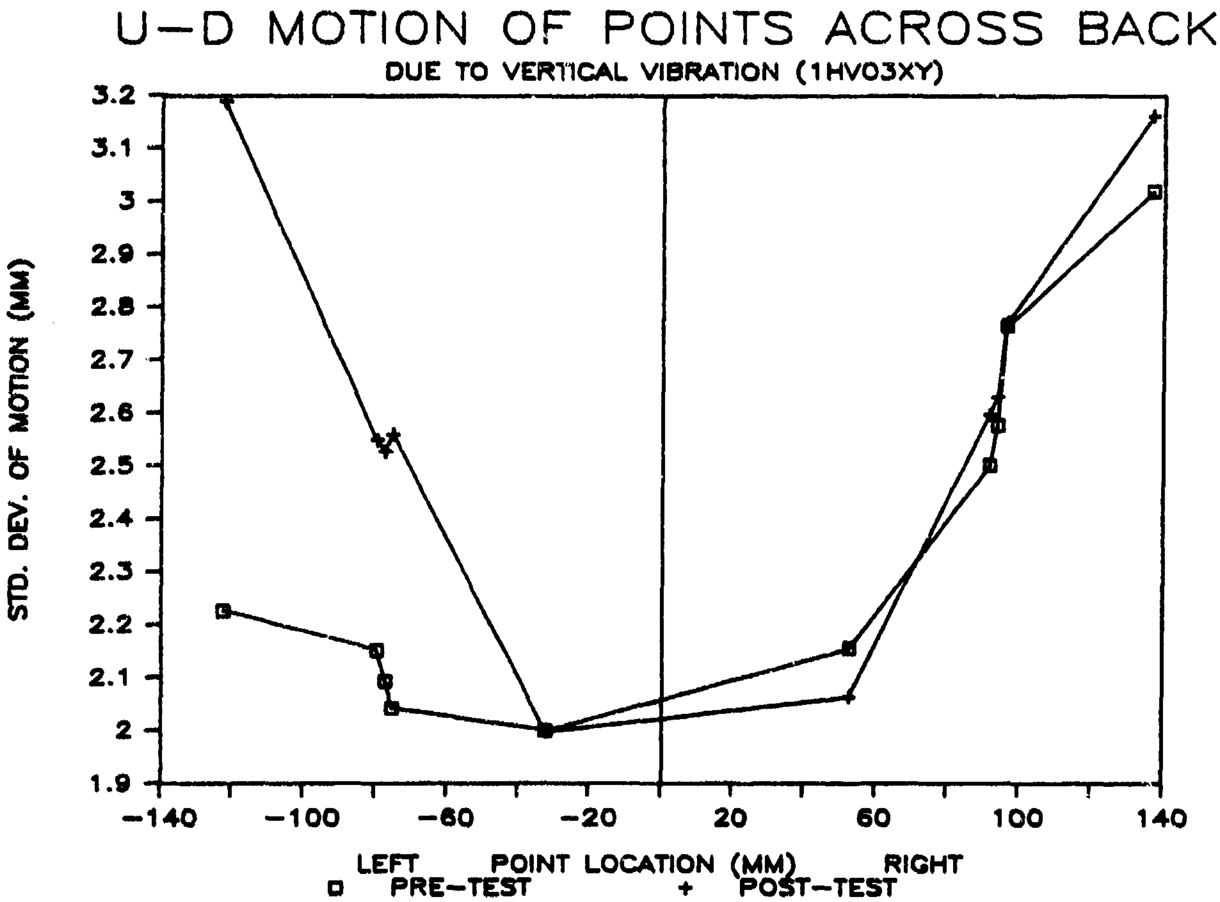


Figure 60. Standard deviation of the up-down positions of each of the points across the top of the back due to a two-hour exposure to UH-1H specific up-down vibration. Data are from subject: 1HV03XY.

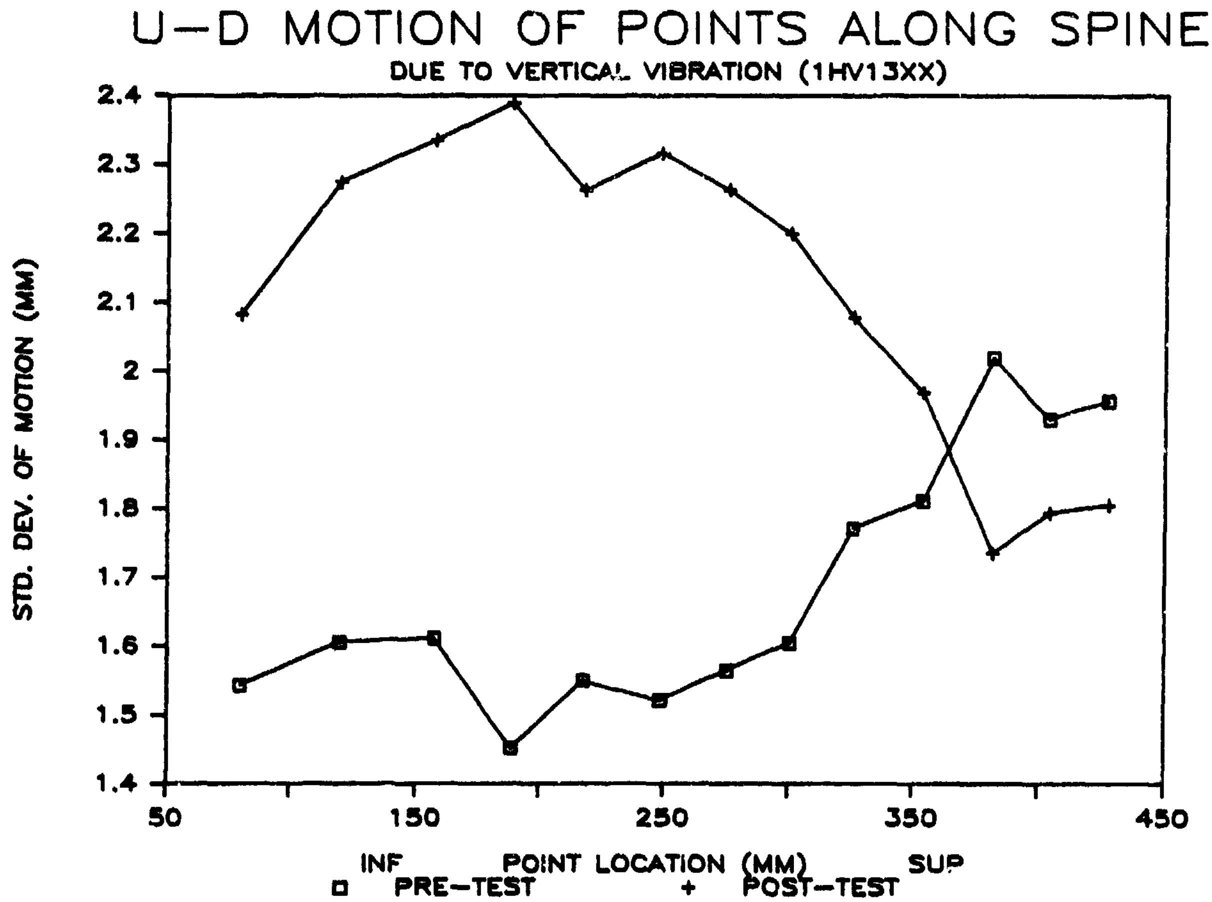


Figure 61. Standard deviation of the up-down positions of each of the points along the spine due to a two-hour exposure to UH-1H specific up-down vibration. Data are from subject: 1HV13XX.

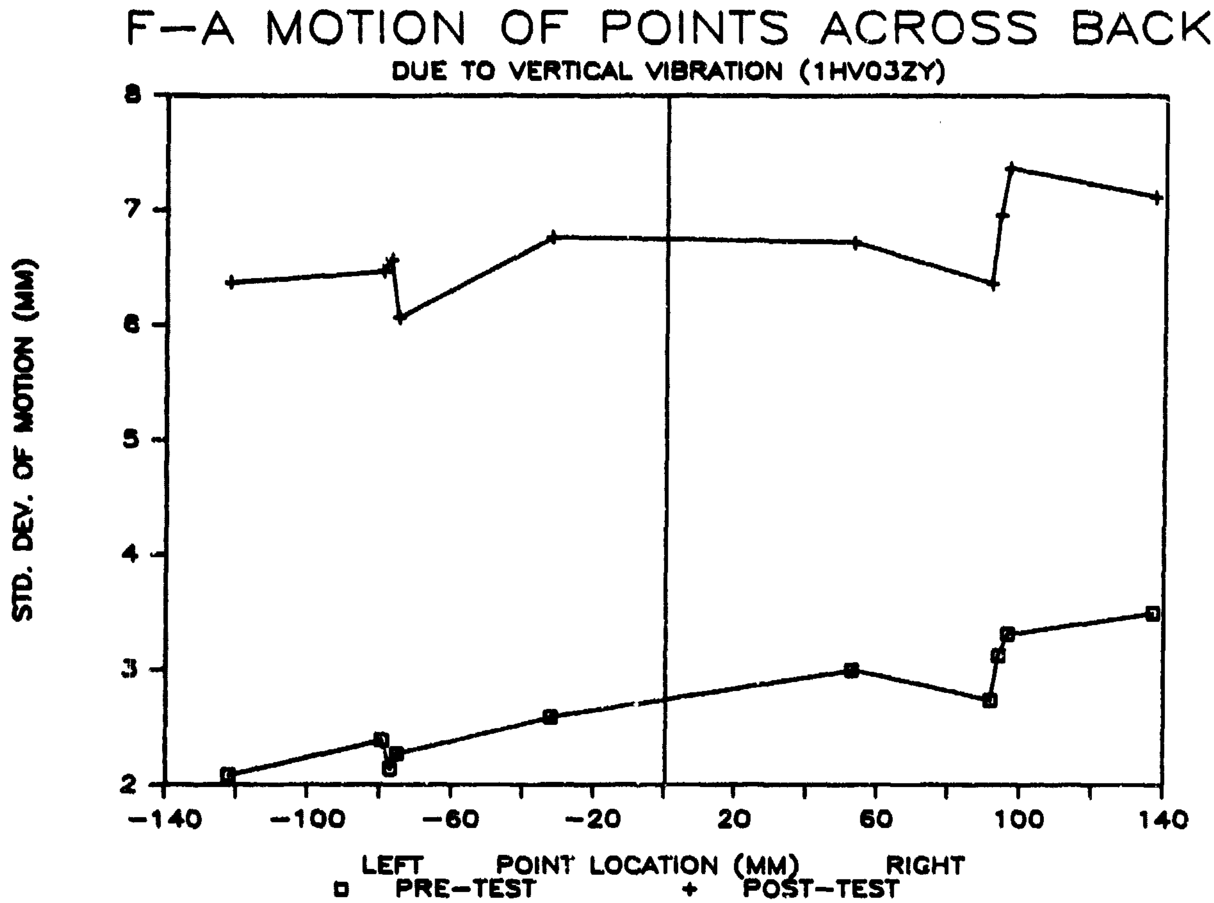


Figure 62. Standard deviation of the fore-aft positions of each of the points across the top of the back due to a two-hour exposure to UH-1H specific up-down vibration. Data are from subject: 1HV03ZY.

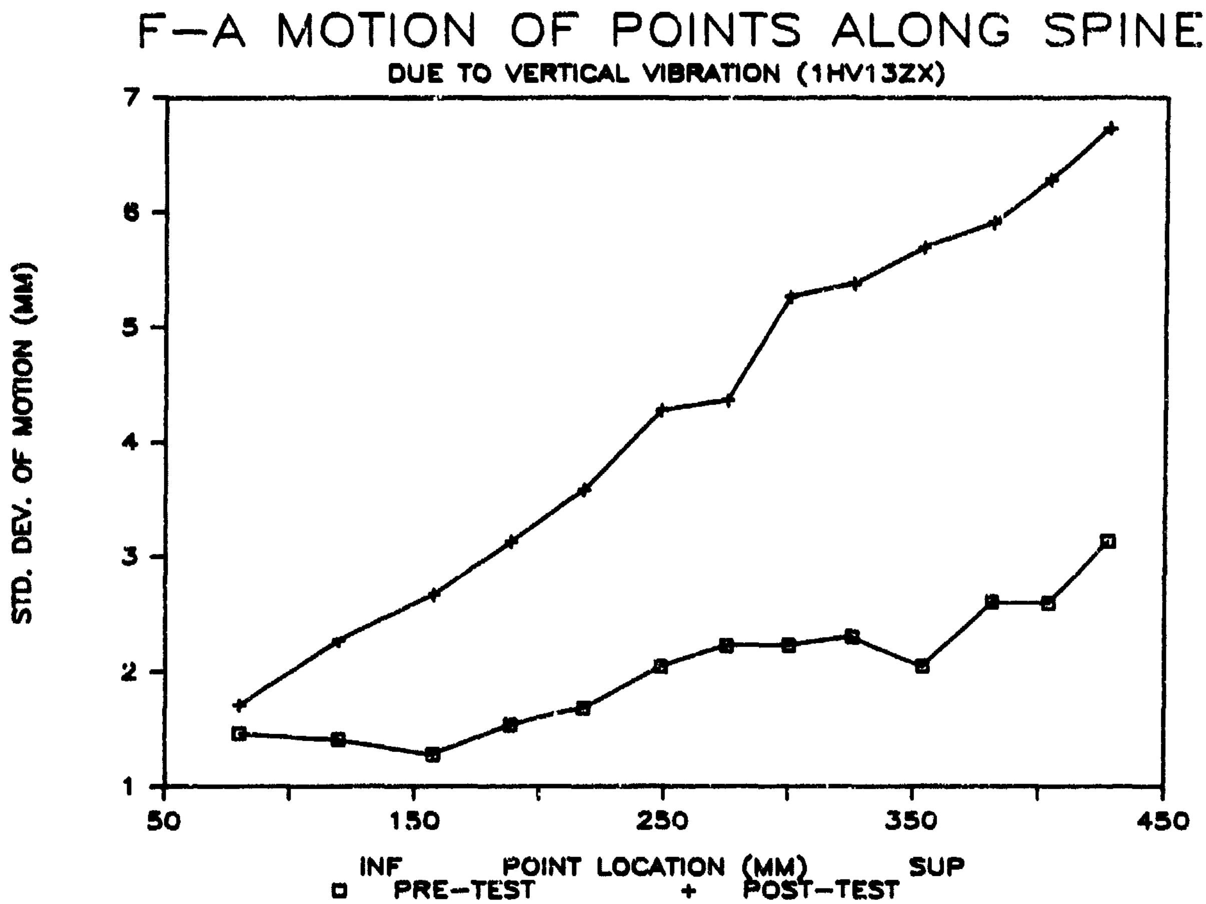


Figure 63. Standard deviation of the fore-aft positions of each of the points along the spine due to a two-hour exposure to UH-1H specific up-down vibration. Data are from subject: 1HV13ZX.

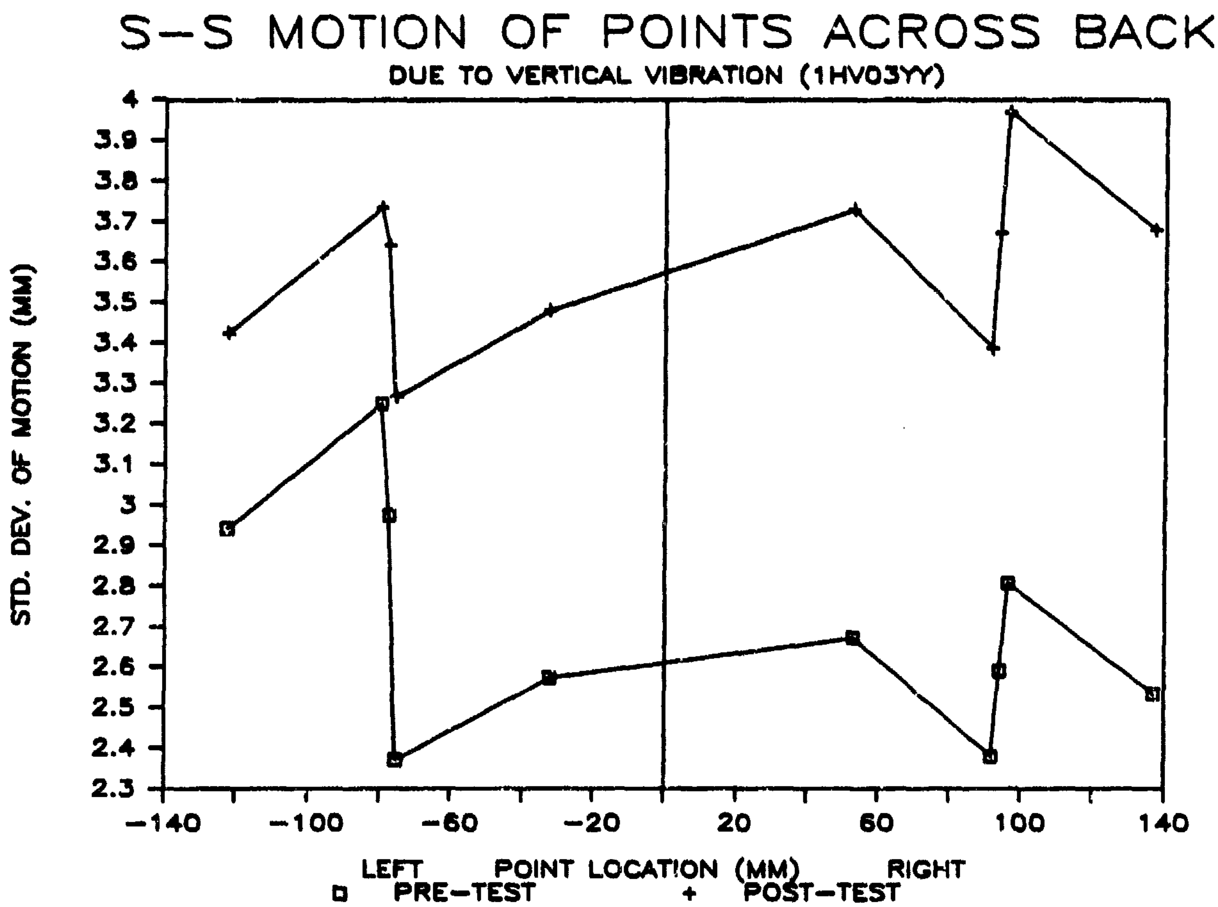


Figure 64. Standard deviation of the side-side positions of each of the points across the top of the back due to a two-hour exposure to UH-1H specific up-down vibration. Data are from subject: 1HV03YY.

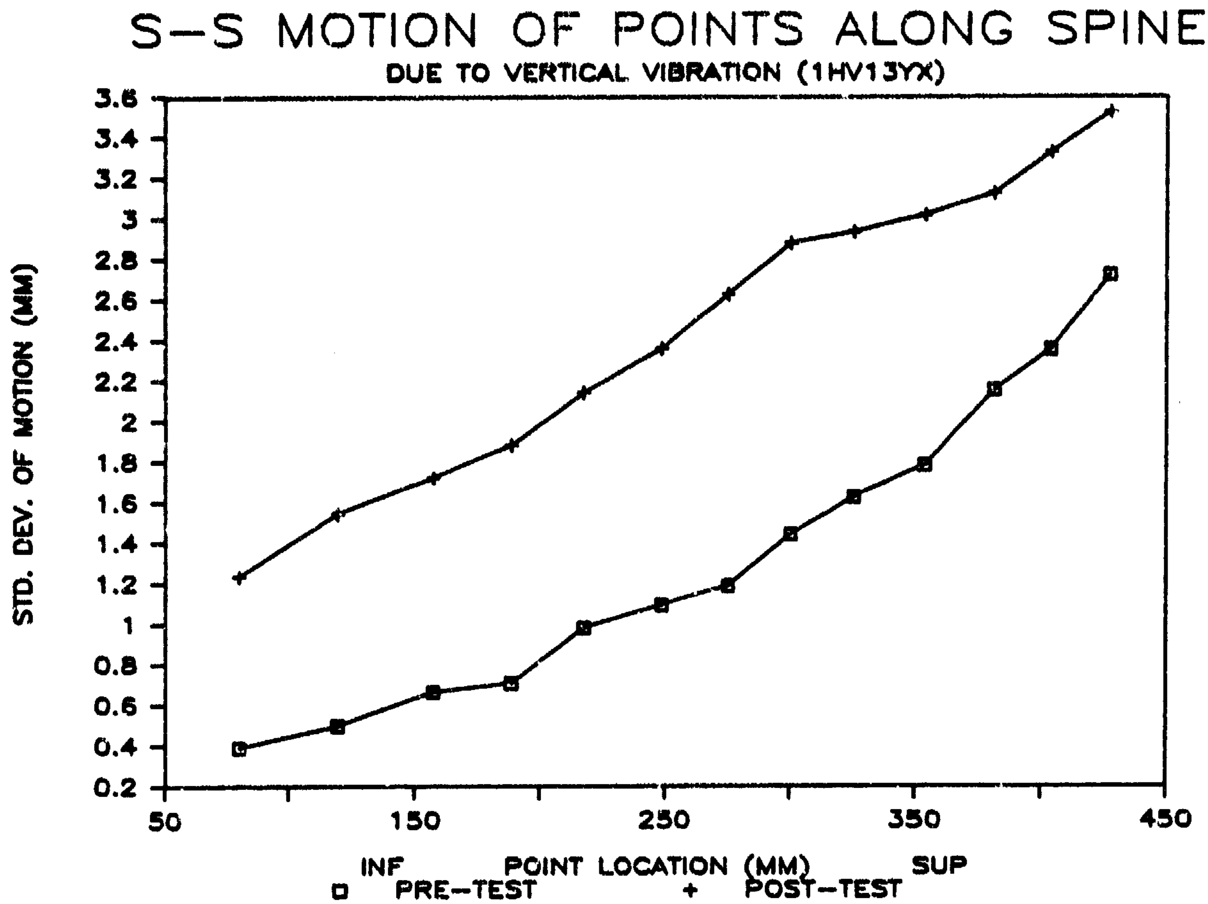


Figure 65. Standard deviation of the side-side positions of each of the points along the spine due to a two-hour exposure to UH-1H specific up-down vibration. Data are from subject: 1HV13YX.

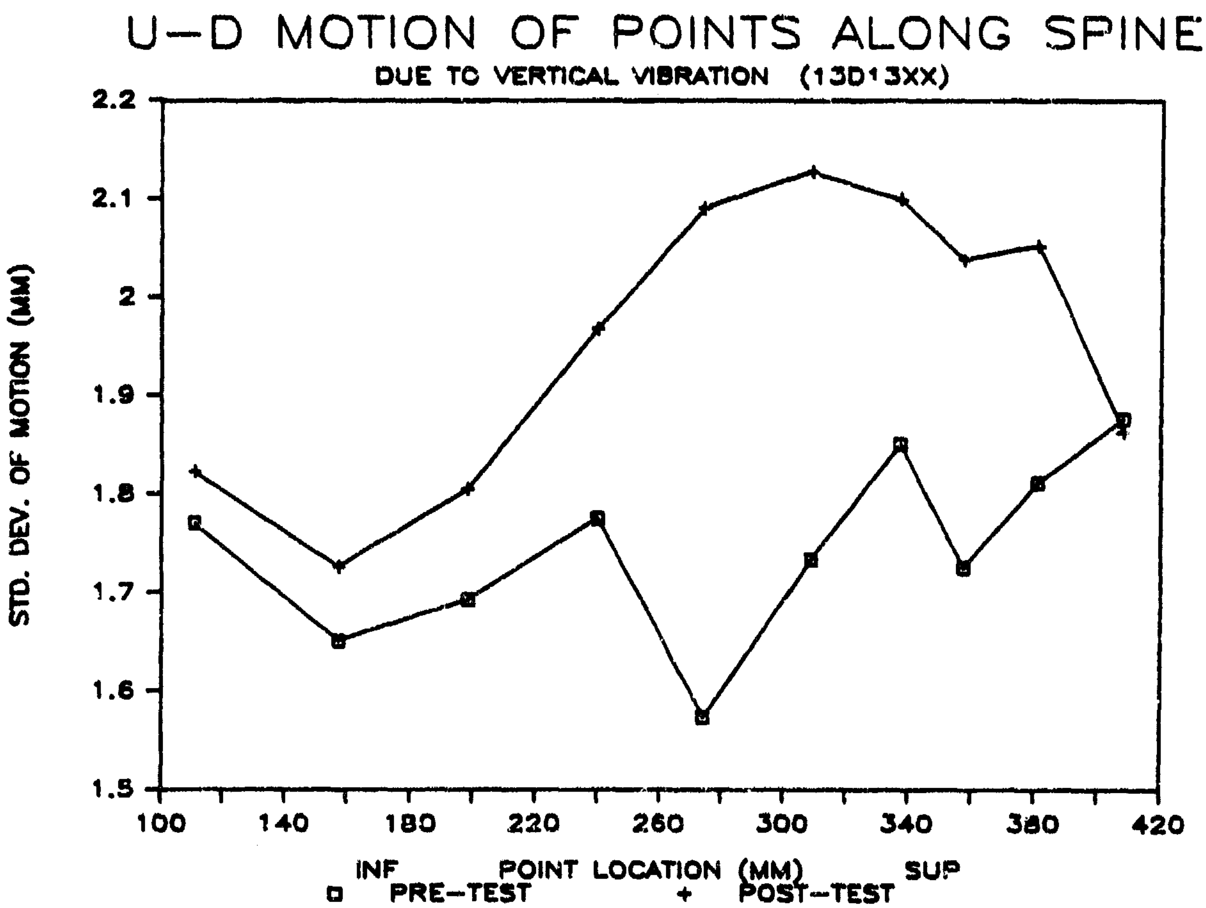


Figure 66. Standard deviation of the up-down positions of each of the points along the spine due to a two-hour exposure to UH-1H specific up-down vibration. Data are from subject: 13D13XX.

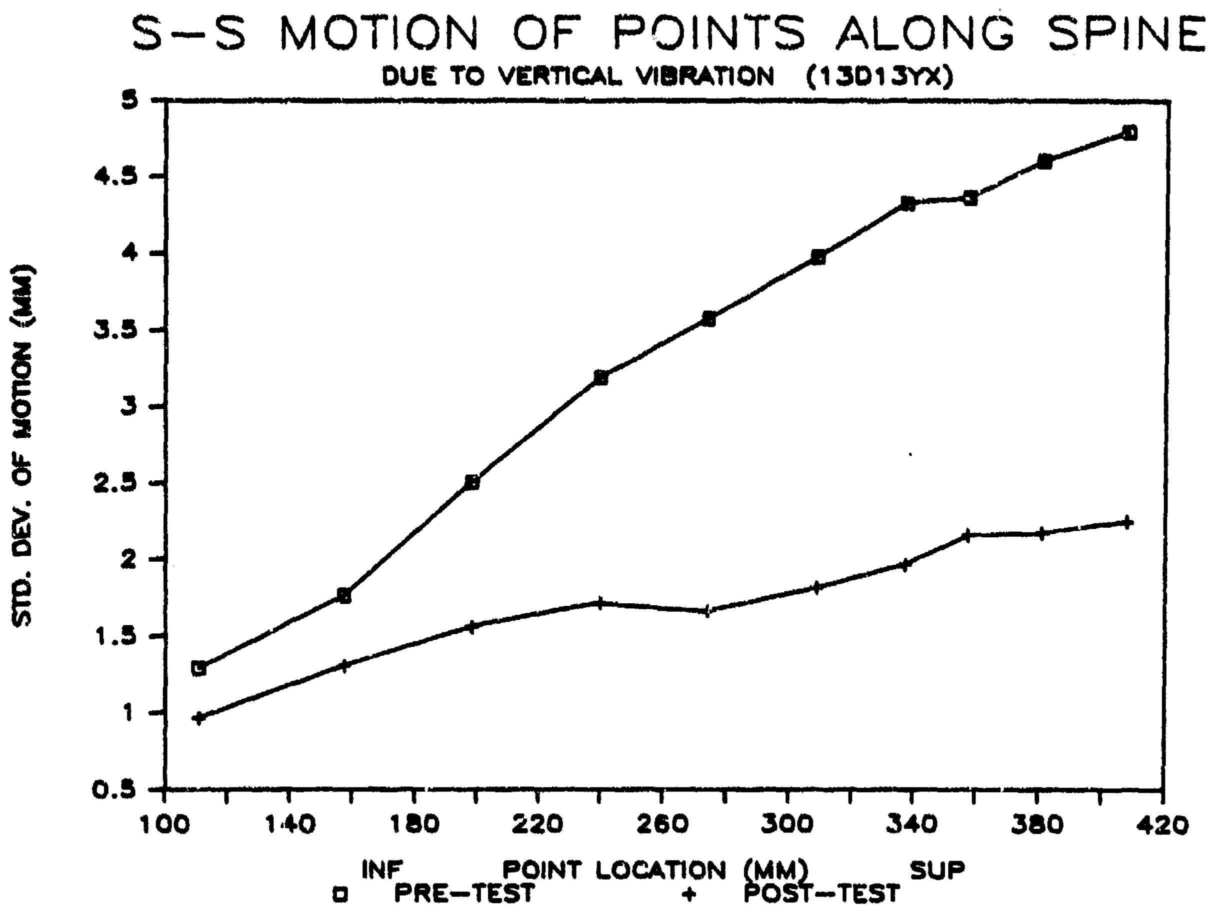


Figure 67. Standard deviation of the side-side positions of each of the points along the spine due to a two-hour exposure to UH-1H specific up-down vibration. Data are from subject: 13D13YX.

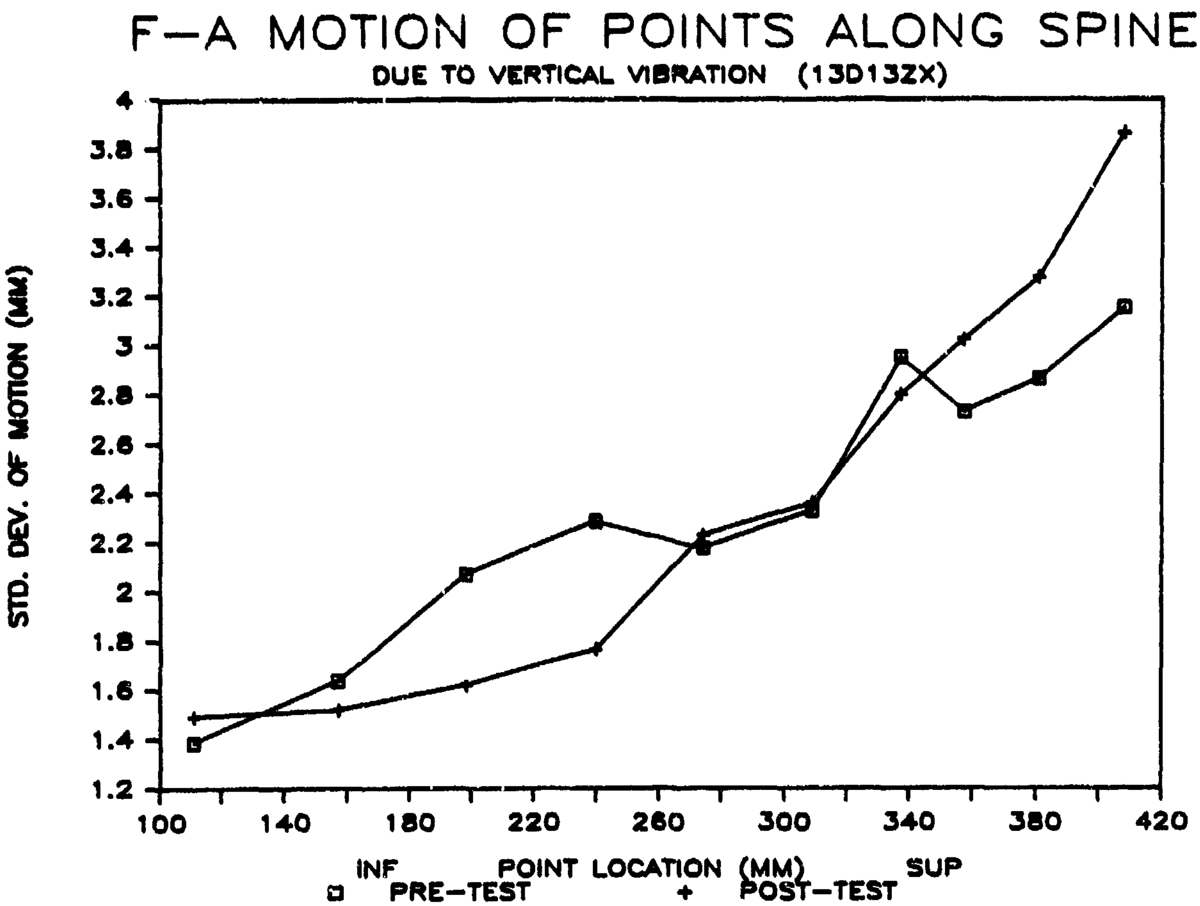


Figure 68. Standard deviation of the fore-aft positions of each of the points along the spine due to a two-hour exposure to UH-1H specific up-down vibration. Data are from subject: 13D13ZX.

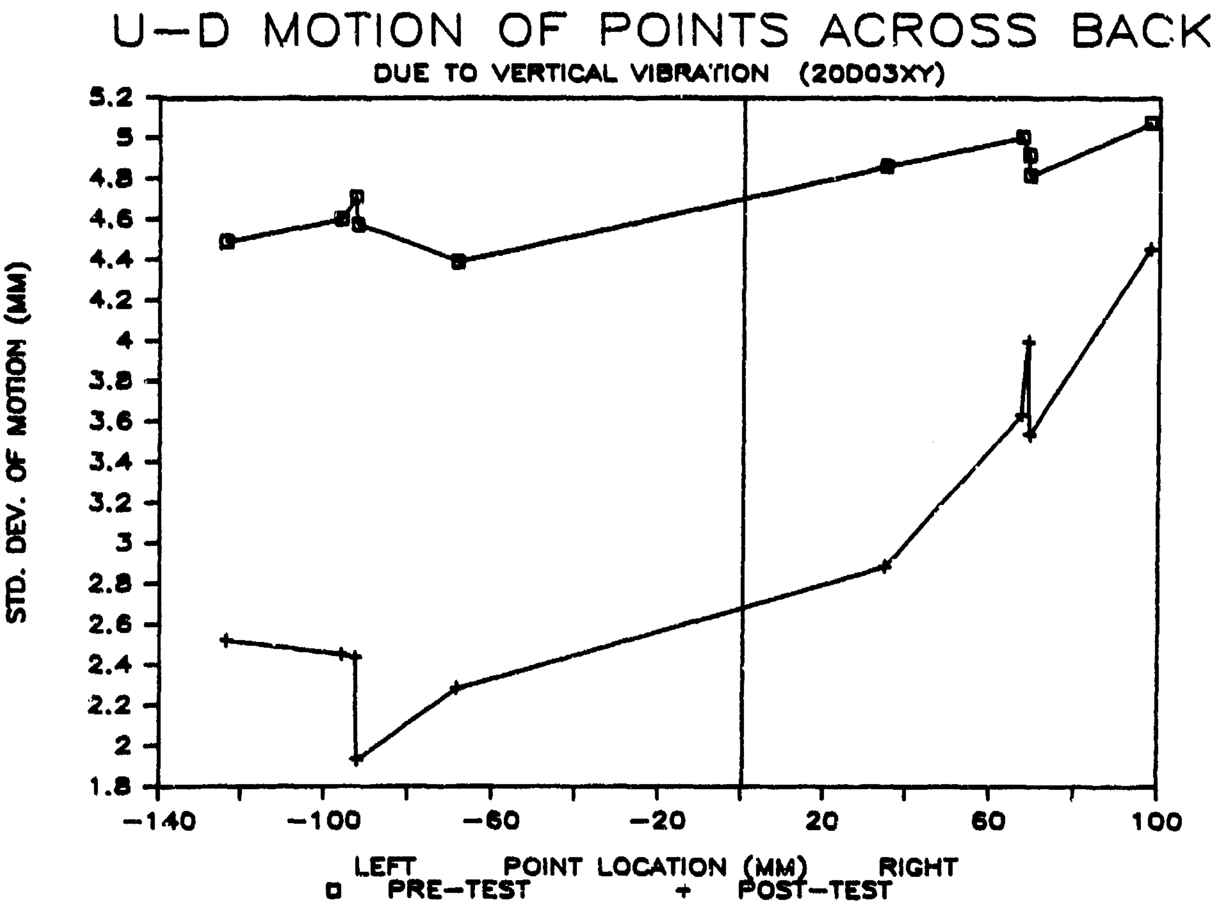


Figure 69. Standard deviation of the up-down positions of each of the points across the top of the back due to a two-hour exposure to UH-1H specific up-down vibration. Data are from subject: 20D03XY.

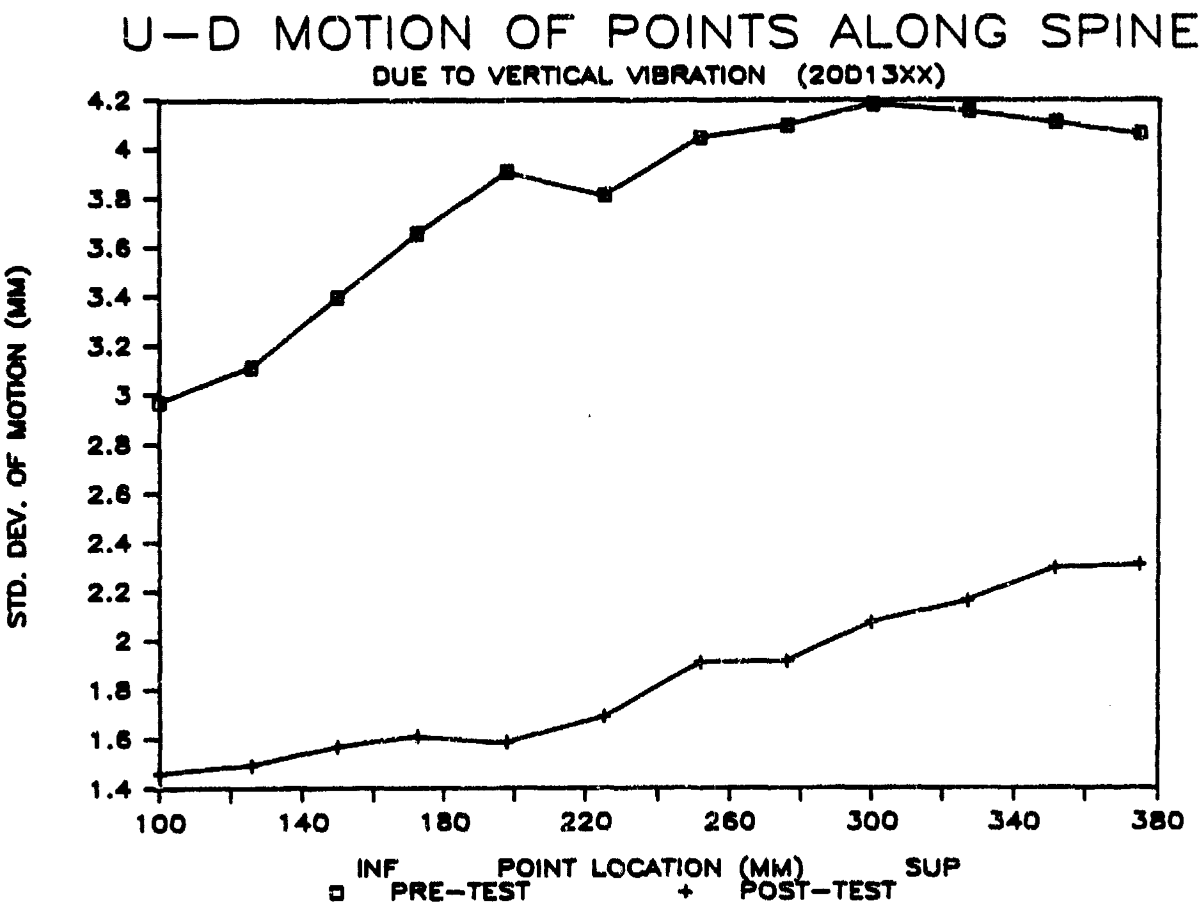


Figure 70. Standard deviation of the up-down positions of each of the points along the spine due to a two-hour exposure to UH-1H specific up-down vibration. Data are from subject: 20D13XX.

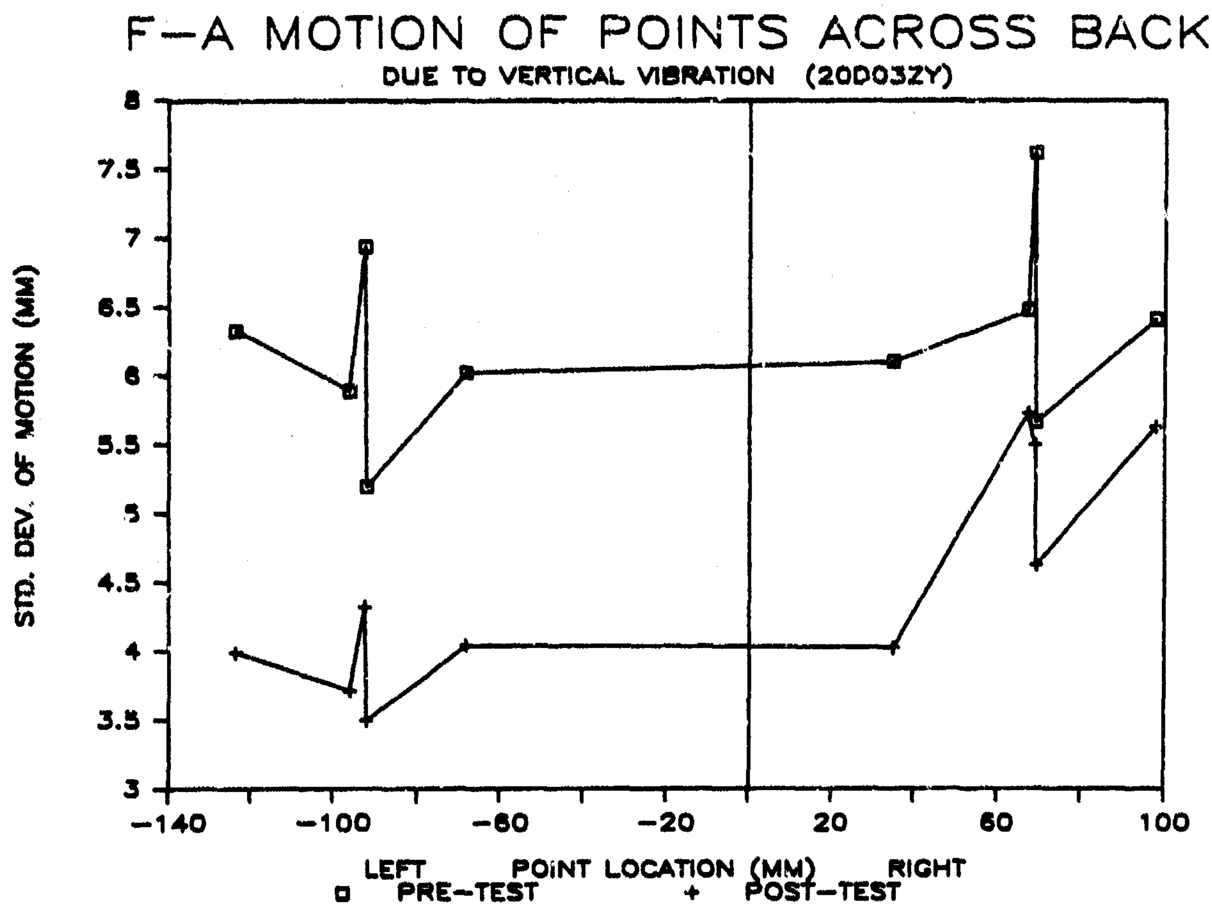


Figure 71. Standard deviation of the fore-aft positions of each of the points across the top of the back due to a two-hour exposure to UH-1H specific up-down vibration. Data are from subject: 20D03ZY.

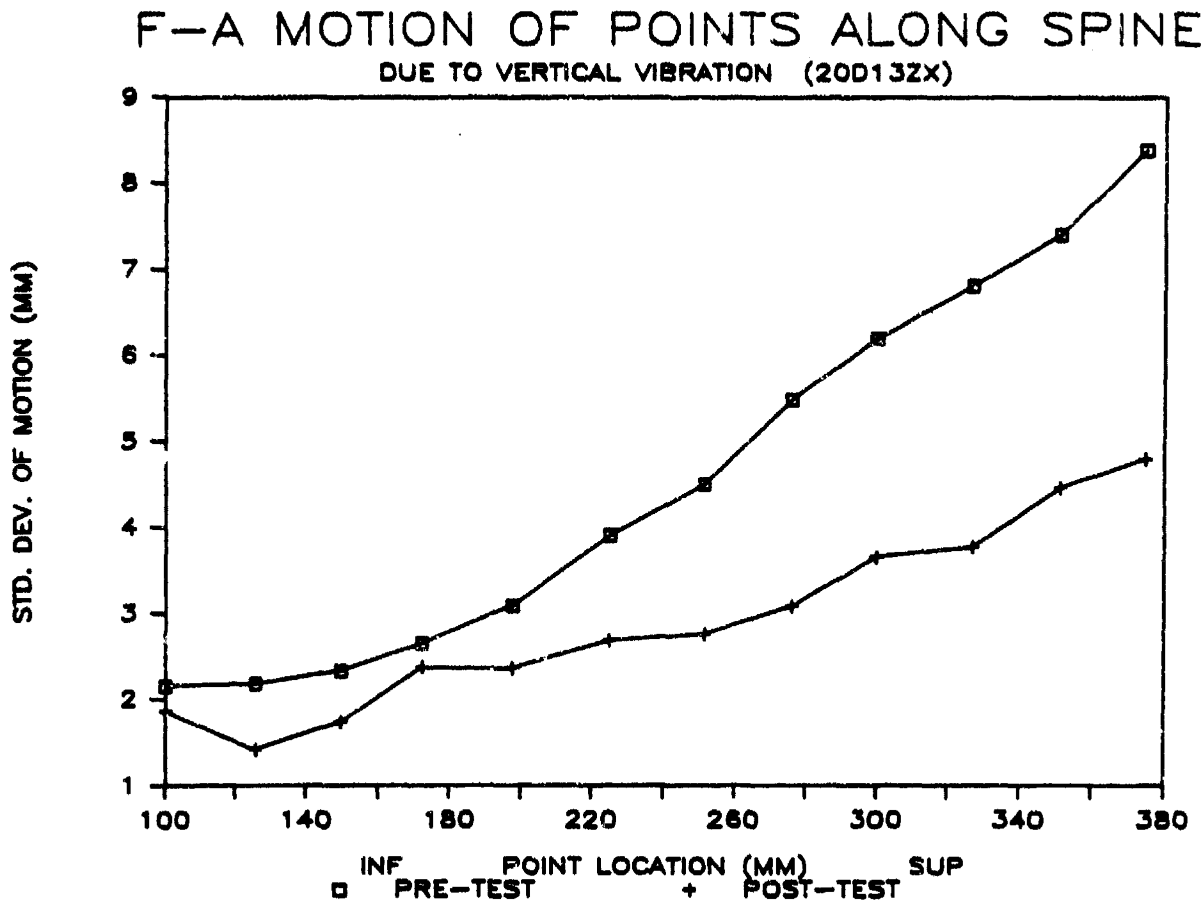


Figure 72. Standard deviation of the fore-aft positions of each of the points along the spine due to a two-hour exposure to UH-1H specific up-down vibration. Data are from subject: 20D13ZX.

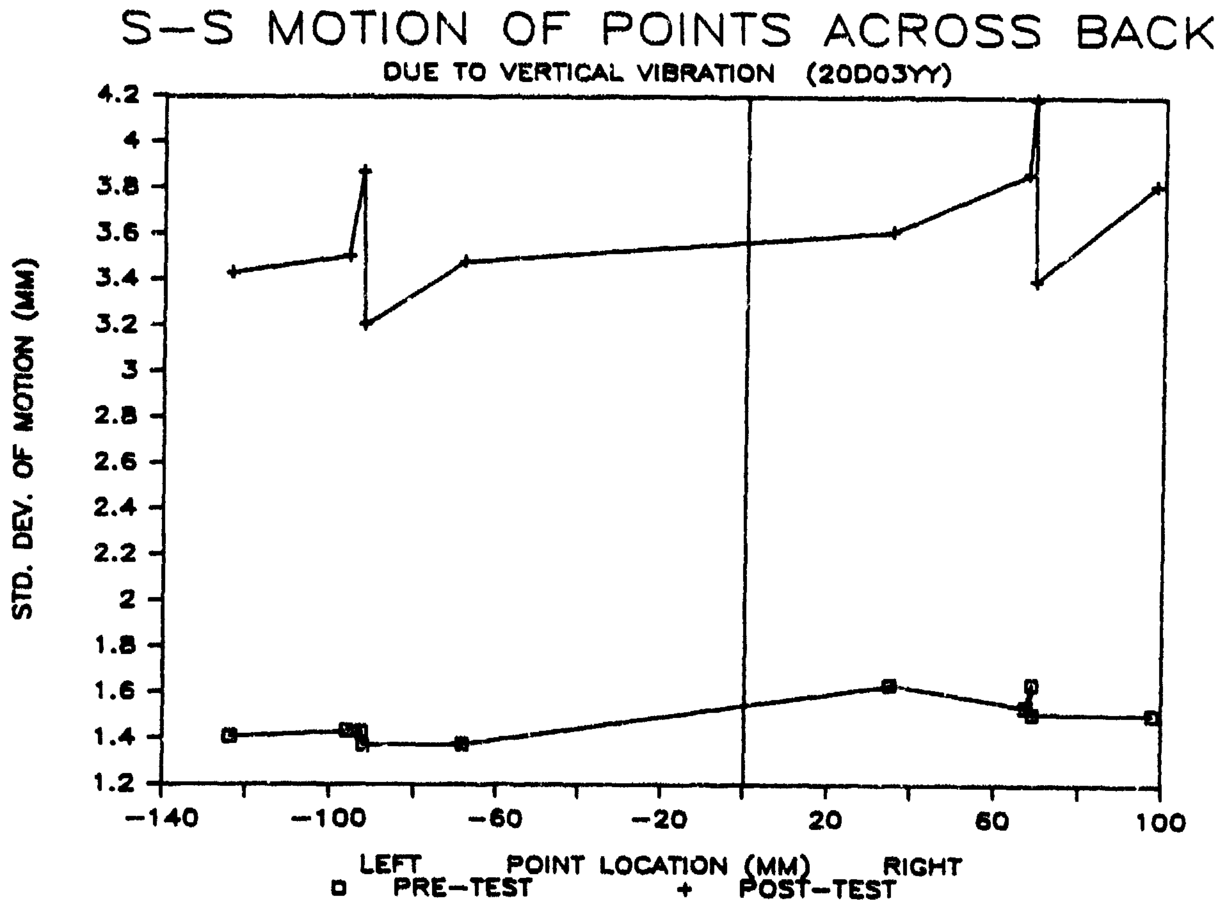


Figure 73. Standard deviation of the side-side positions of each of the points across the top of the back due to a two-hour exposure to UH-1H specific up-down vibration. Data are from subject: 20D03YY.

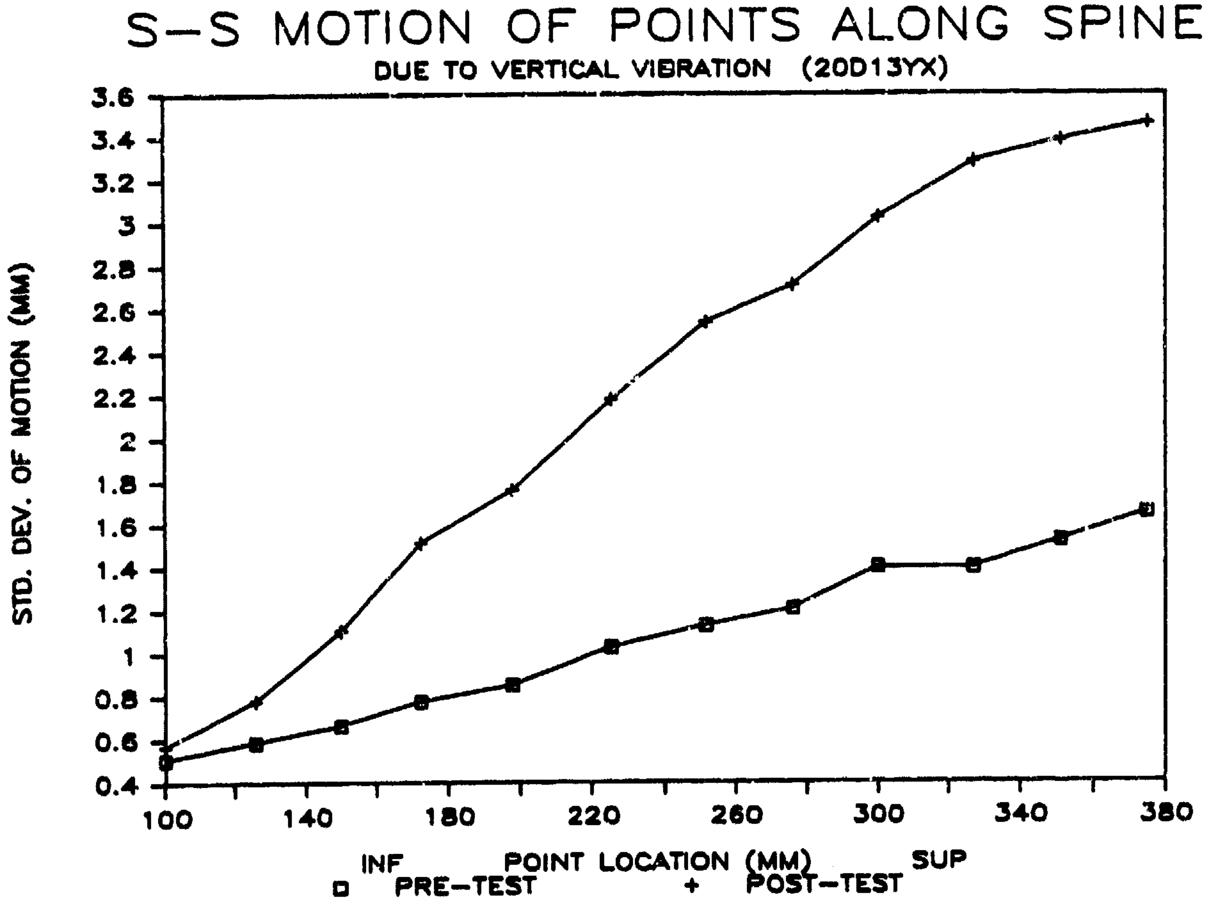


Figure 74. Standard deviation of the side-side positions of each of the points along the spine due to a two-hour exposure to UH-1H specific up-down vibration. Data are from subject: 20D13YX.

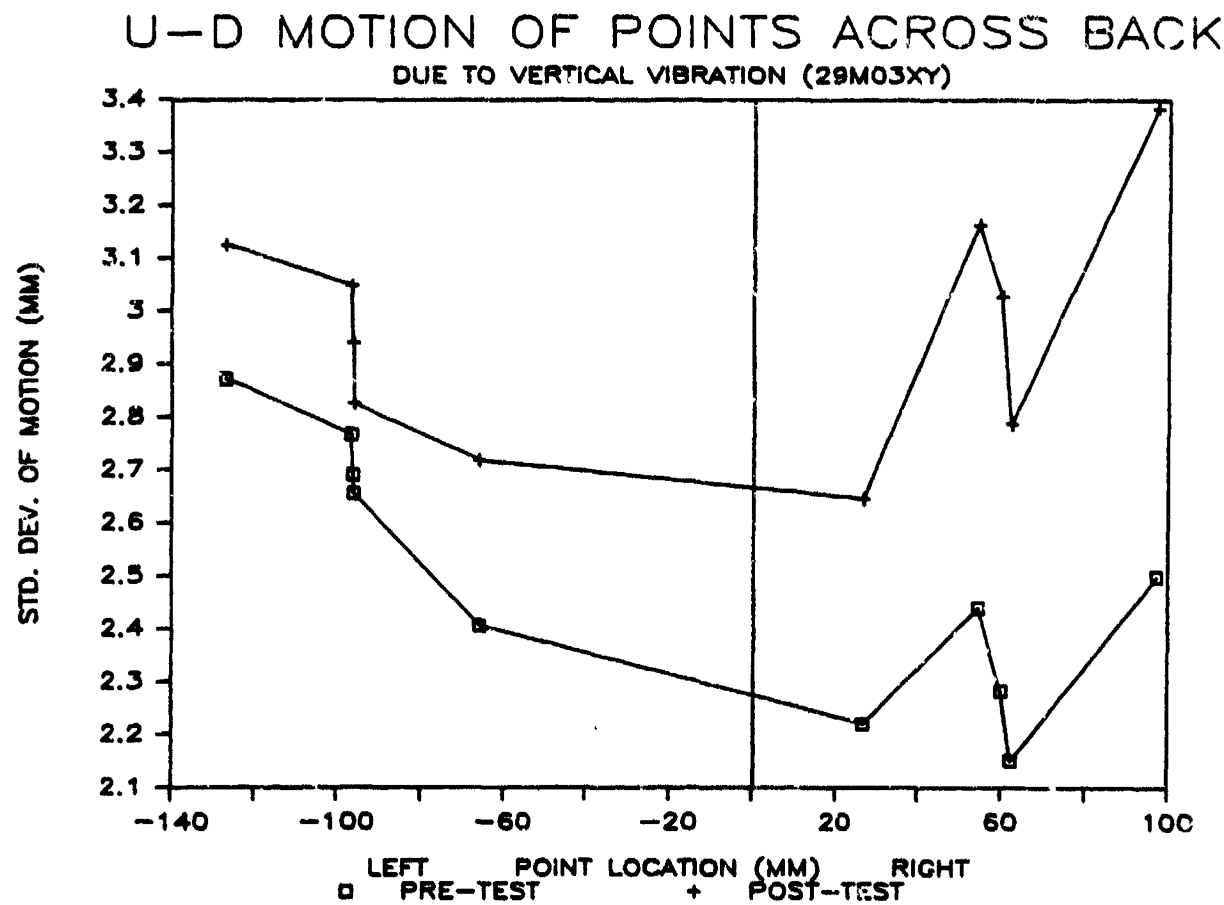


Figure 75. Standard deviation of the up-down positions of each of the points across the top of the back due to a two-hour exposure to UH-1H specific up-down vibration. Data are from subject: 29M03XY.

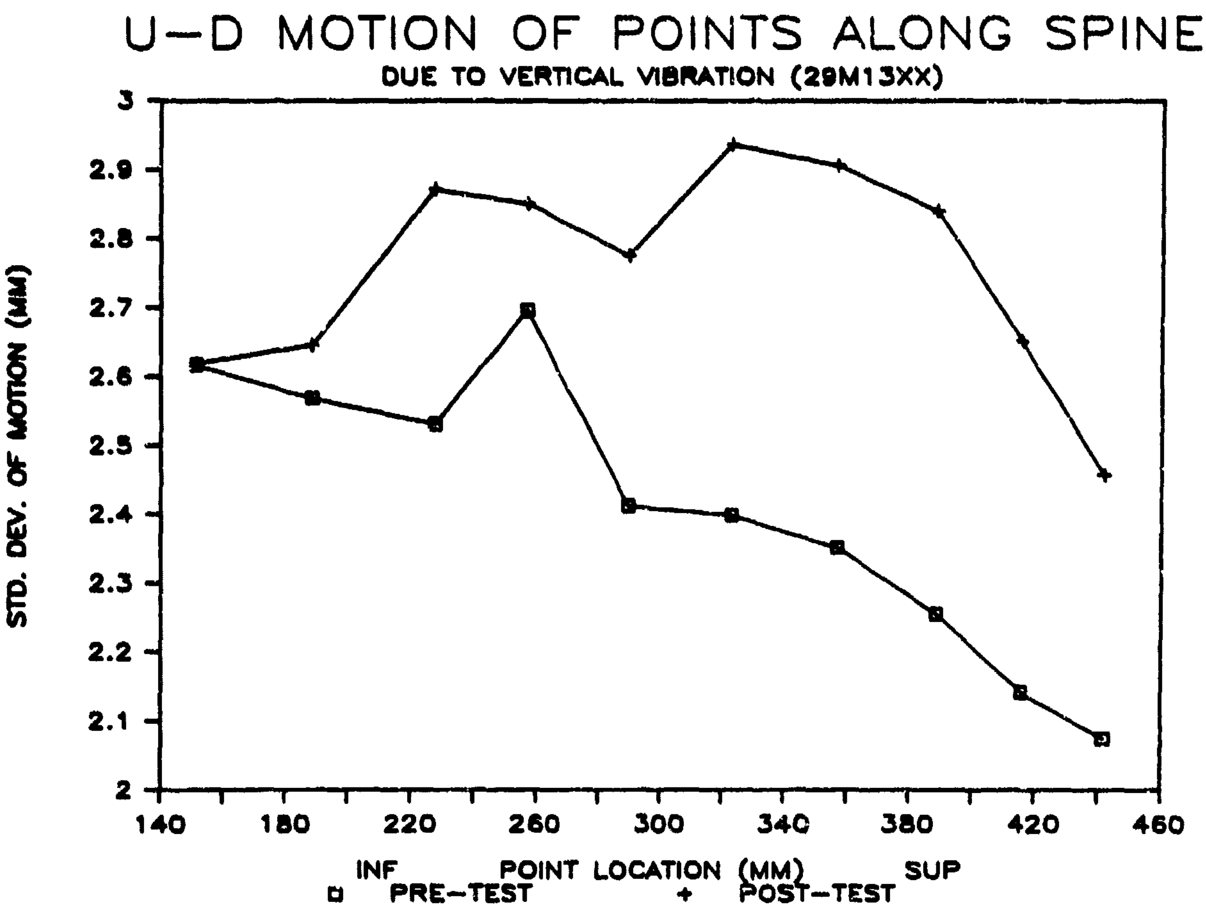


Figure 76. Standard deviation of the up-down positions of each of the points along the spine due to a two-hour exposure to UH-1H specific up-down vibration. Data are from subject: 29M13XX.

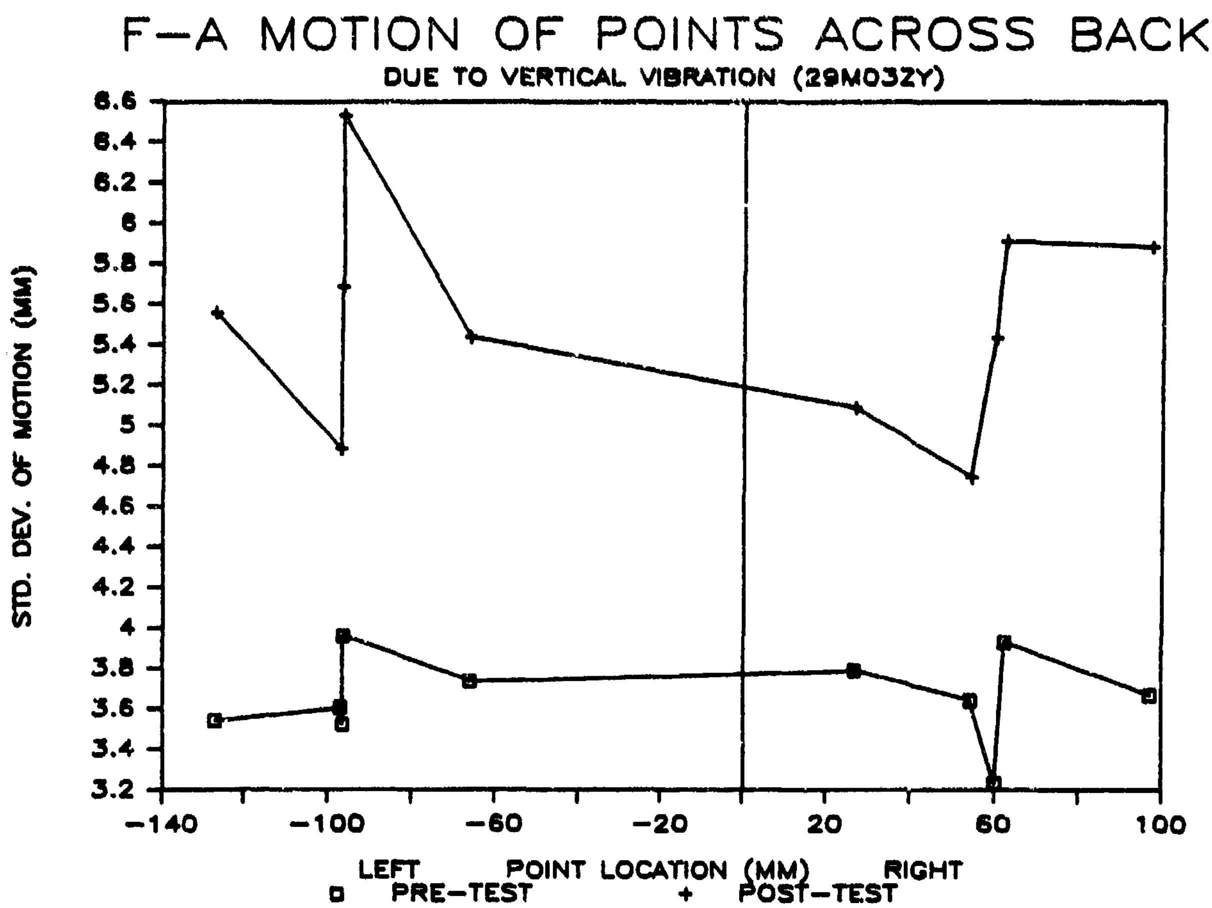


Figure 77. Standard deviation of the fore-aft positions of each of the points across the top of the back due to a two-hour exposure to UH-1H specific up-down vibration. Data are from subject: 29M03ZY.

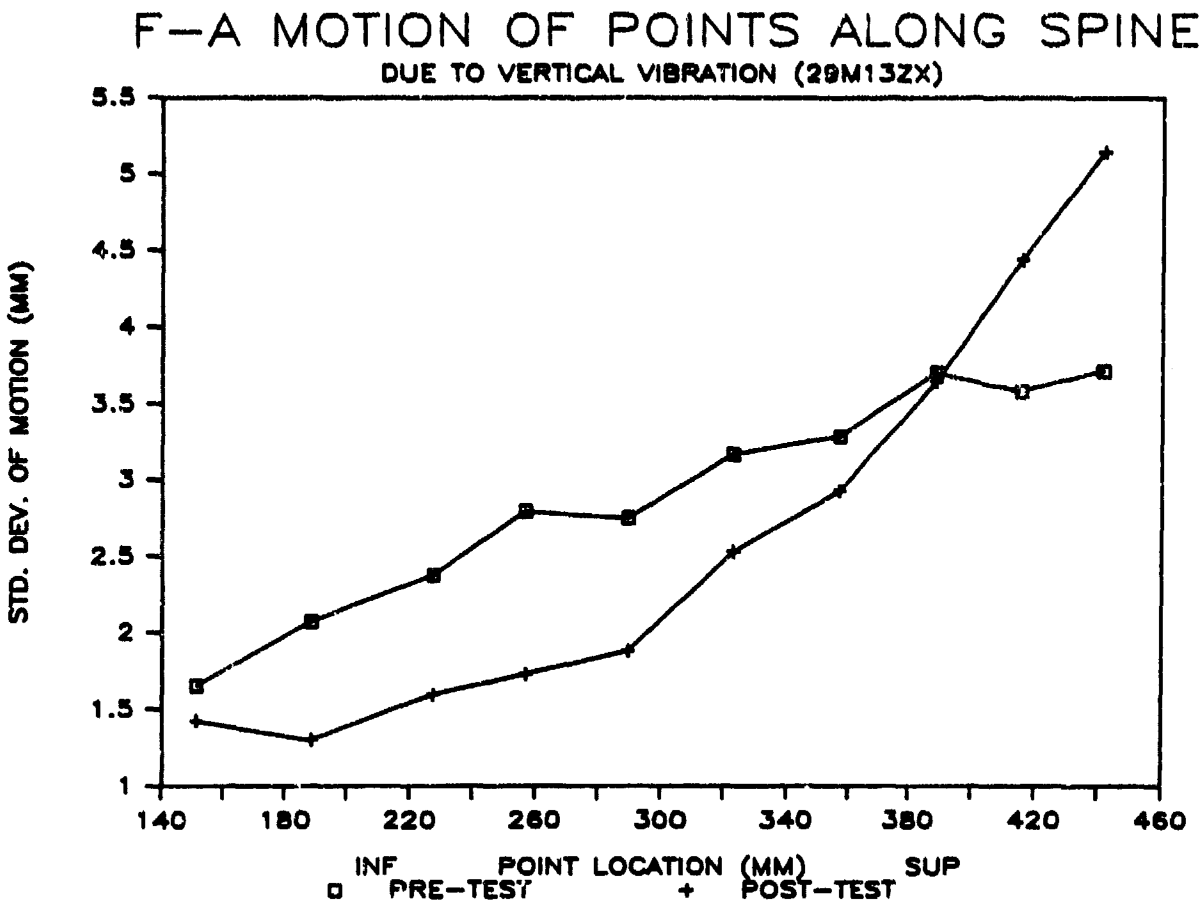


Figure 78. Standard deviation of the fore-aft positions of each of the points along the spine due to a two-hour exposure to UH-1H specific up-down vibration. Data are from subject: 29M13ZX.

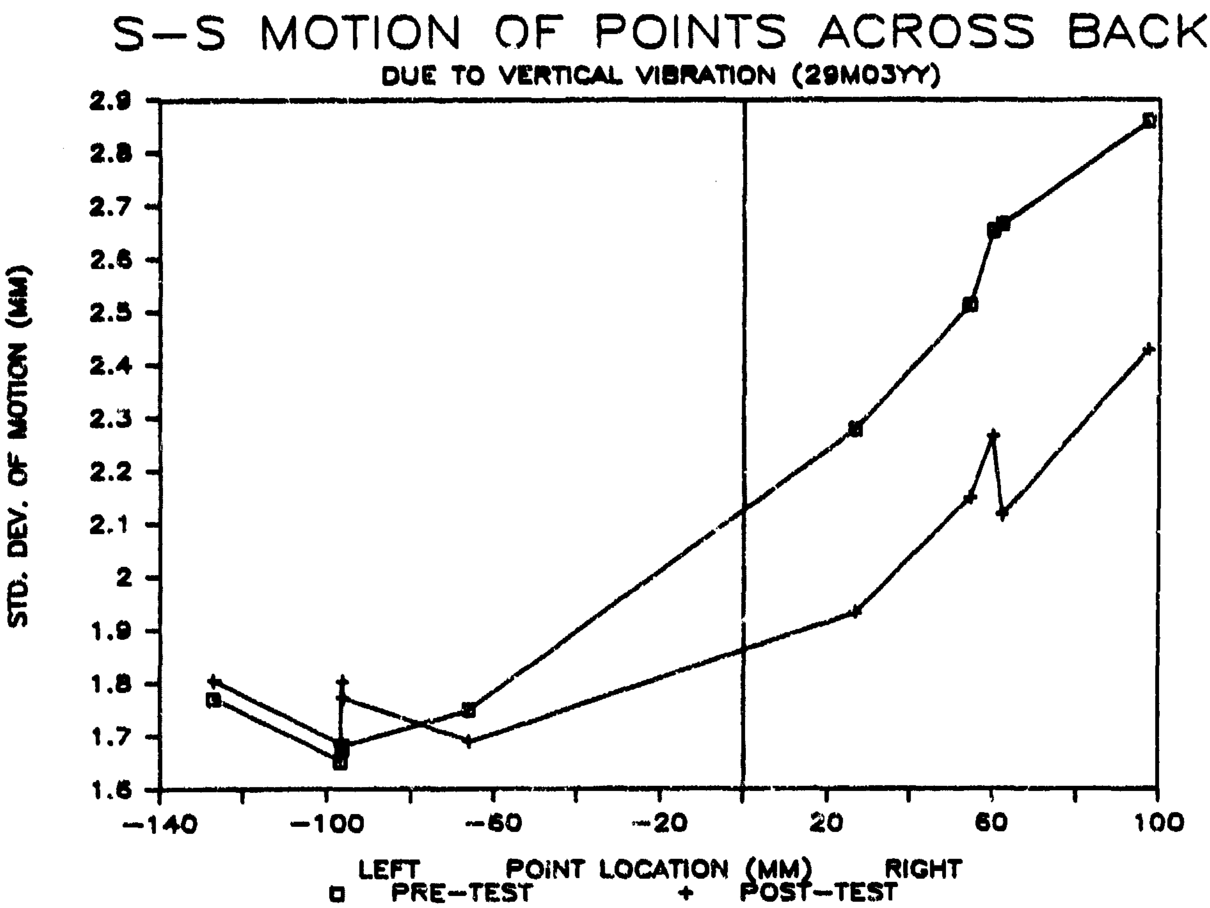


Figure 79. Standard deviation of the side-side positions of each of the points across the top of the back due to a two-hour exposure to UH-1H specific up-down vibration. Data are from subject: 29MC3YY.

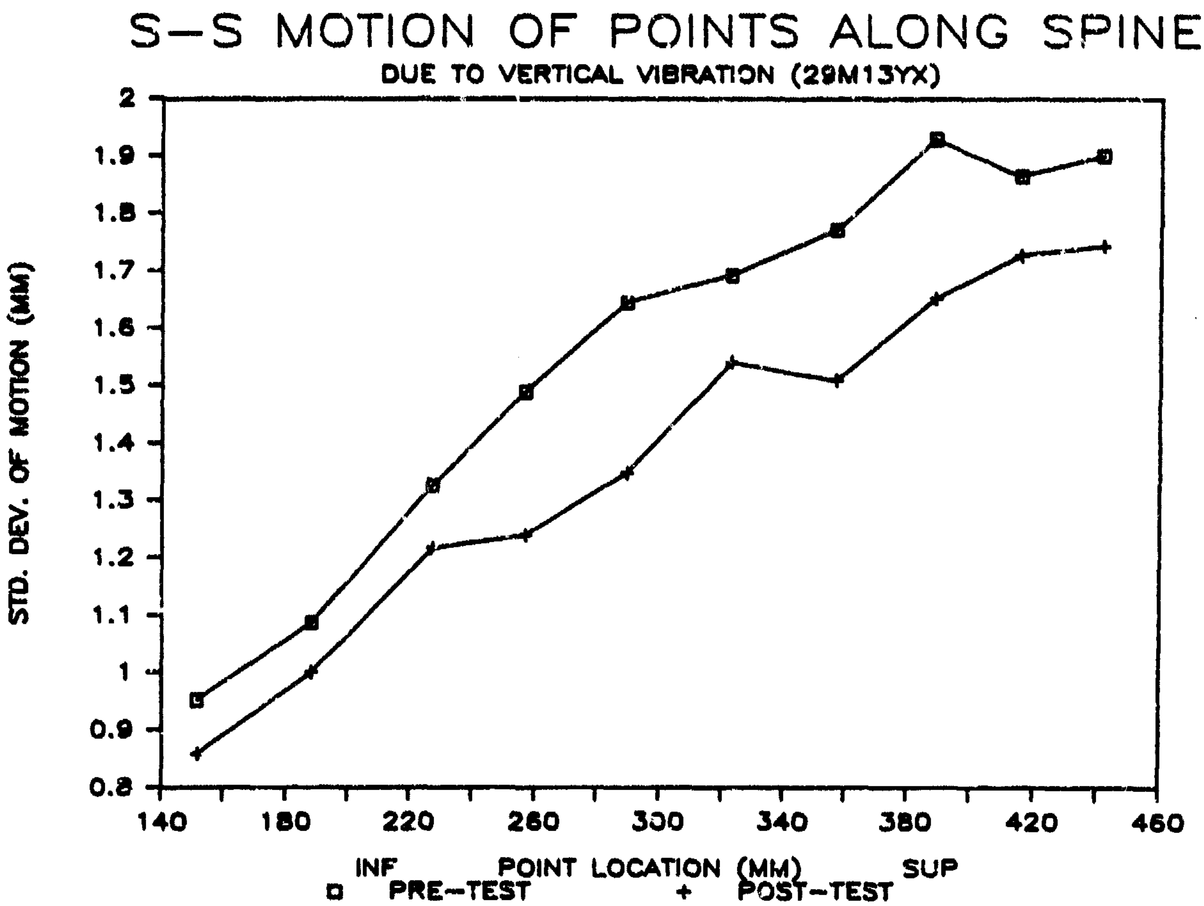


Figure 80. Standard deviation of the side-side positions of each of the points along the spine due to a two-hour exposure to UH-1H specific up-down vibration. Data are from subject: 29M13YX.

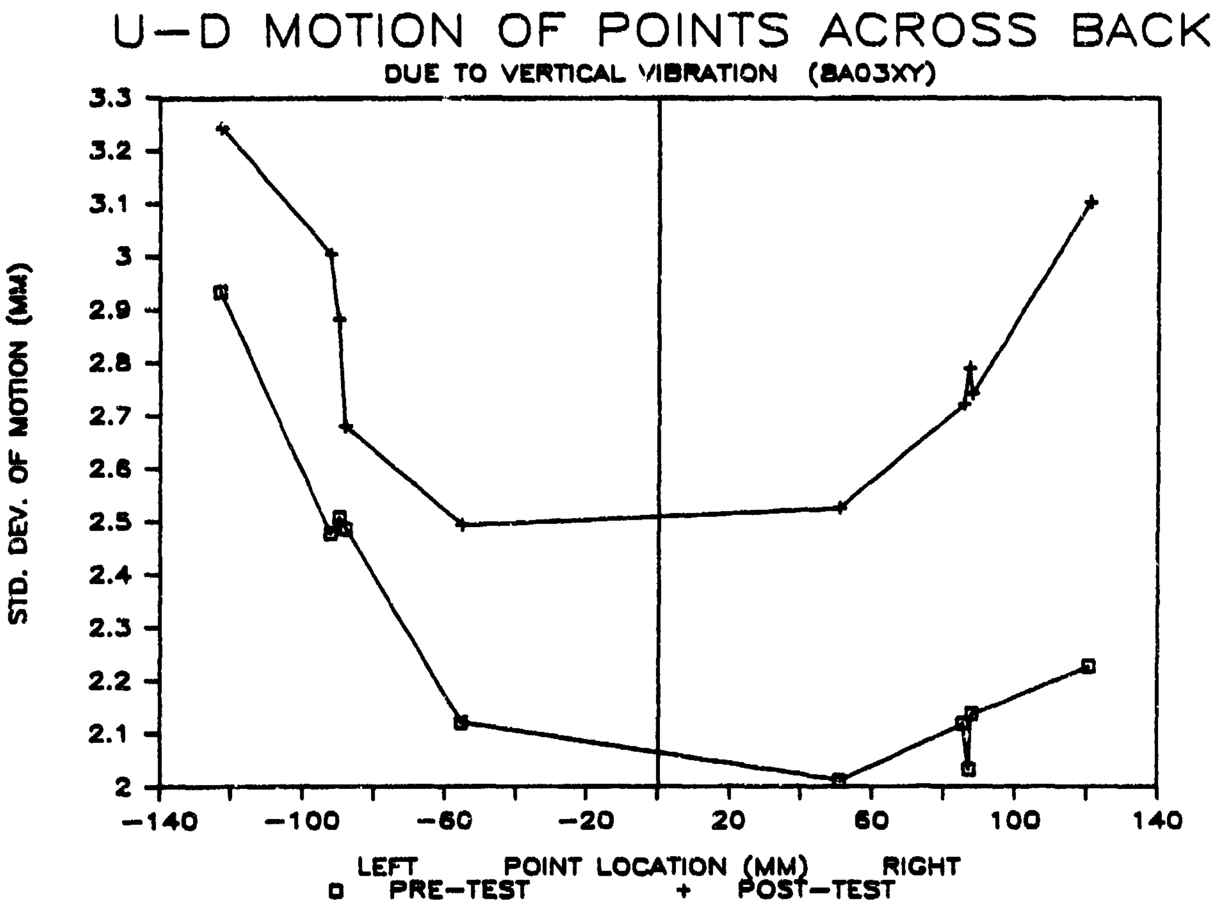


Figure 81. Standard deviation of the up-down positions of each of the points across the top of the back due to a two-hour exposure to UH-1H specific up-down vibration. Data are from subject: 8A03XY.

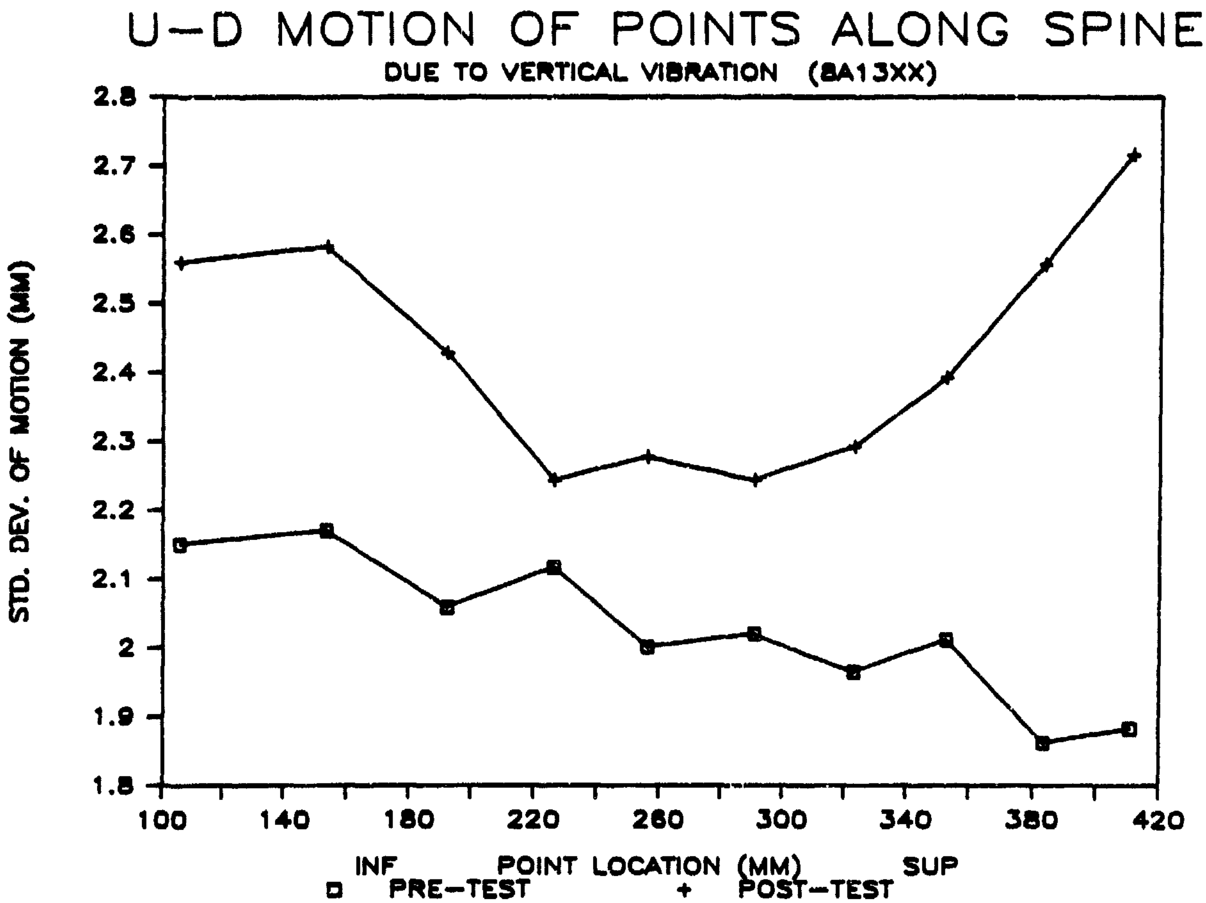


Figure 82. Standard deviation of the up-down positions of each of the points along the spine due to a two-hour exposure to UH-1H specific up-down vibration. Data are from subject: 8A13XX.

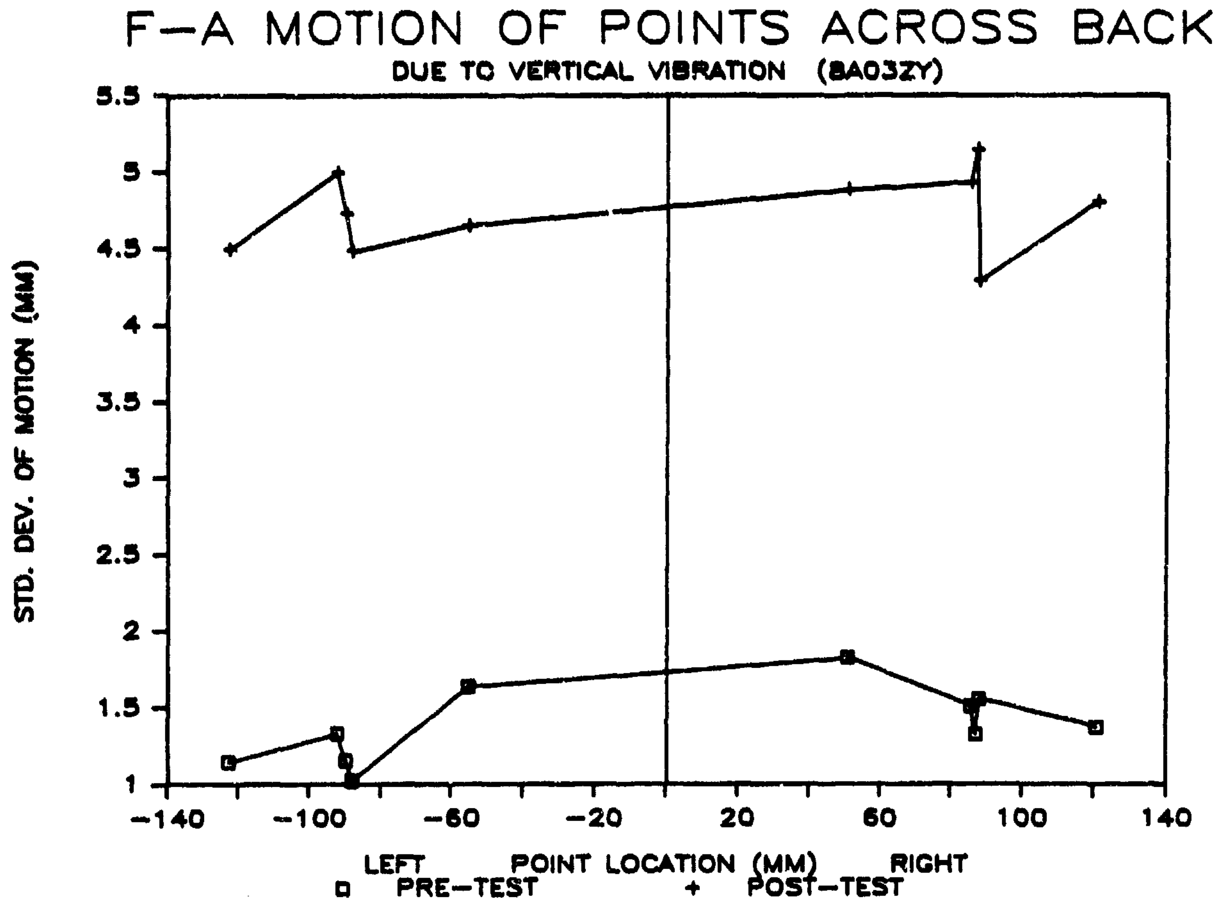


Figure 83. Standard deviation of the fore-aft positions of each of the points across the top of the back due to a two-hour exposure to UH-1H specific up-down vibration. Data are from subject: 8A03ZY.

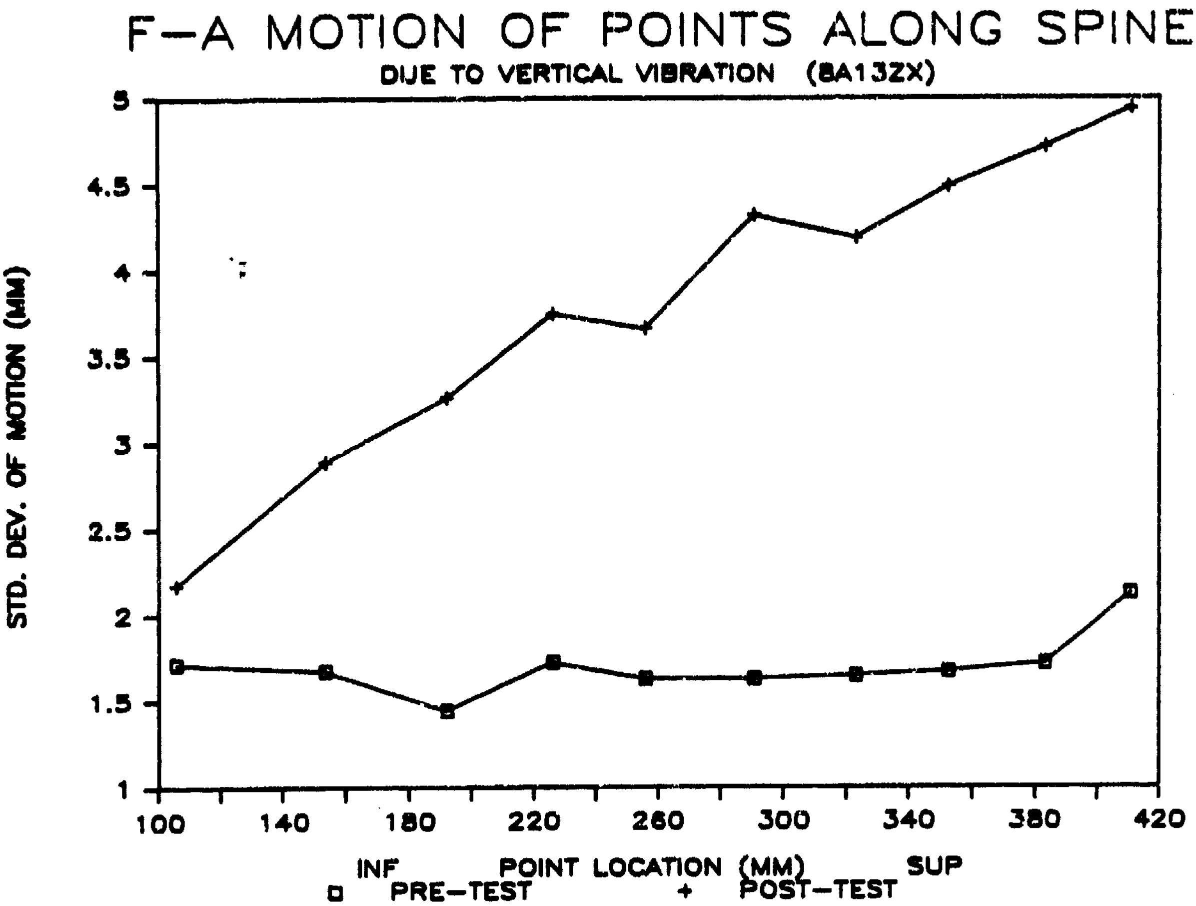


Figure 84. Standard deviation of the fore-aft positions of each of the points along the spine due to a two-hour exposure to UH-1H specific up-down vibration. Data are from subject: 8A13ZX.

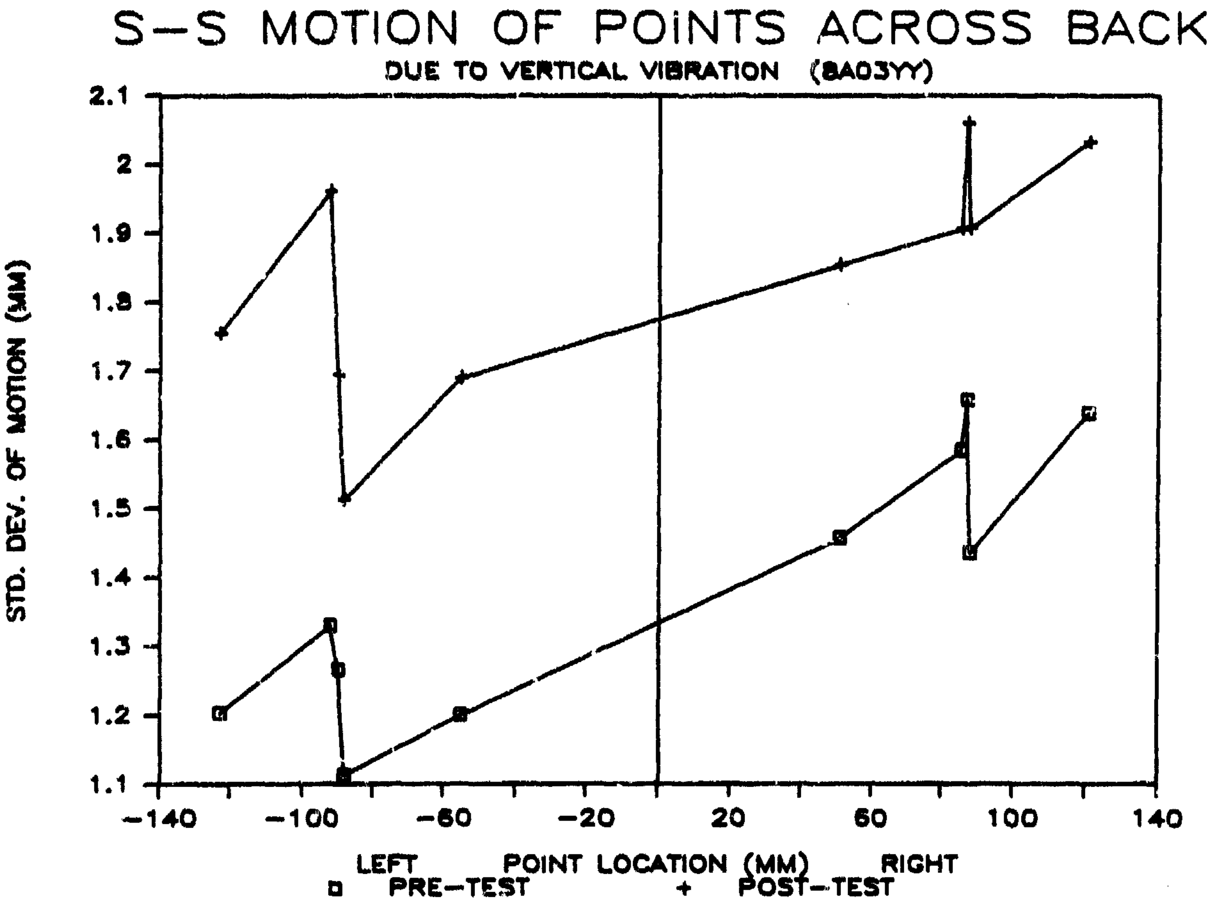


Figure 85. Standard deviation of the side-side positions of each of the points across the top of the back due to a two-hour exposure to UH-1H specific up-down vibration. Data are from subject: 8A03YY.

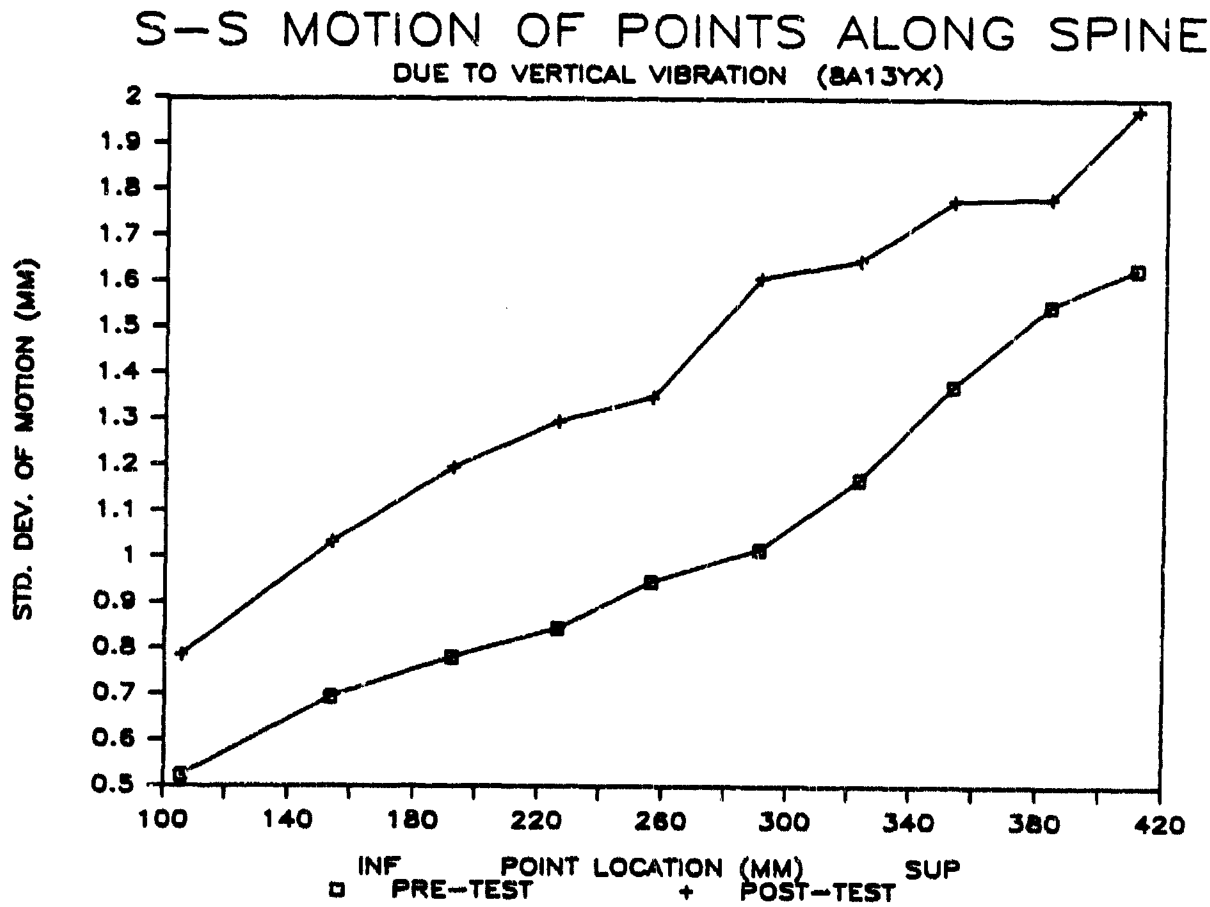


Figure 86. Standard deviation of the side-side positions of each of the points along the spine due to a two-hour exposure to UH-1H specific up-down vibration. Data are from subject: 8A13YX.

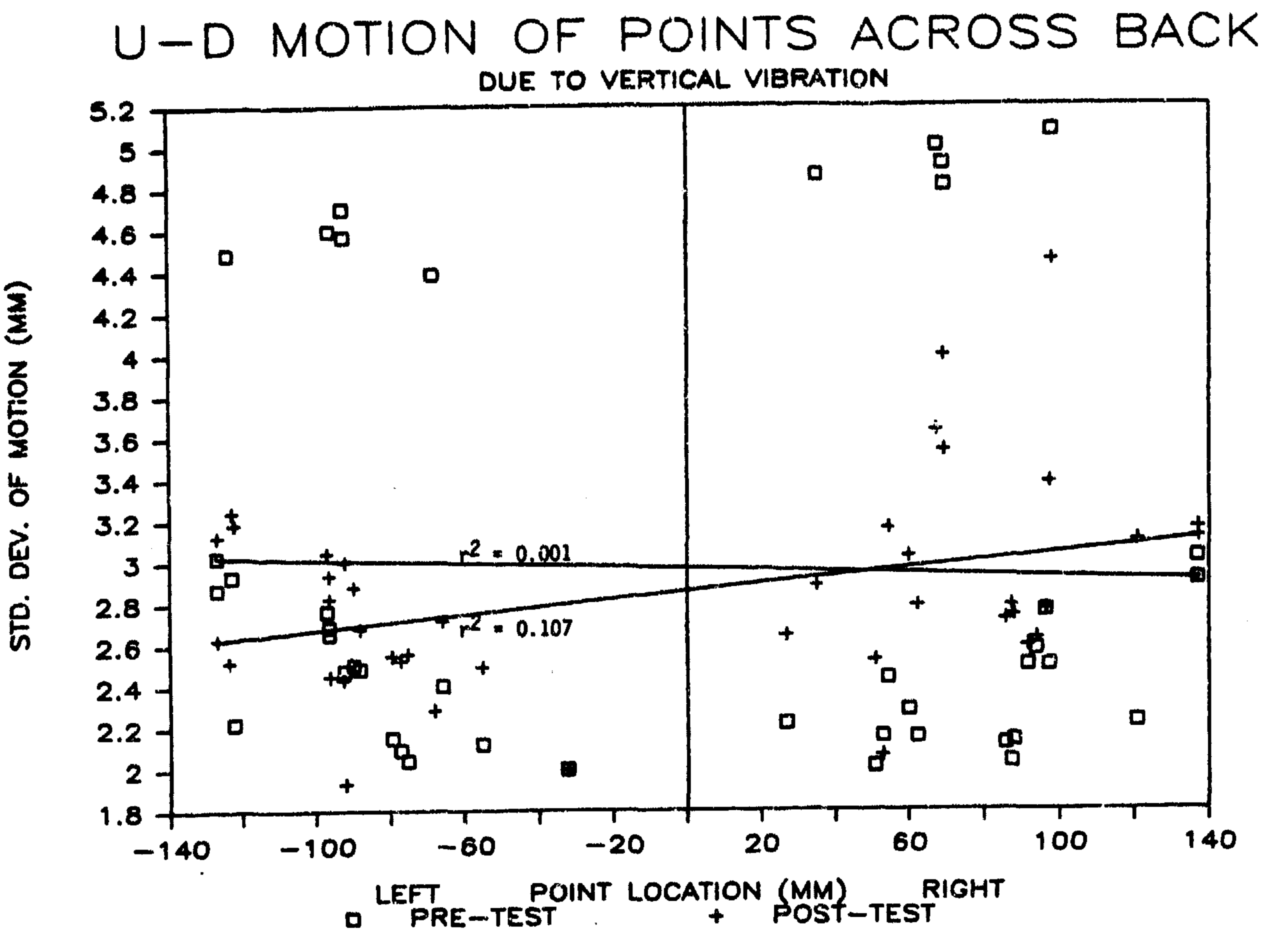


Figure 87. Linear regression of standard deviation of the up-down positions of each of the points across the top of the back with their location across the back due to a two-hour exposure to UH-1H specific up-down vibration. Data are from four subjects.

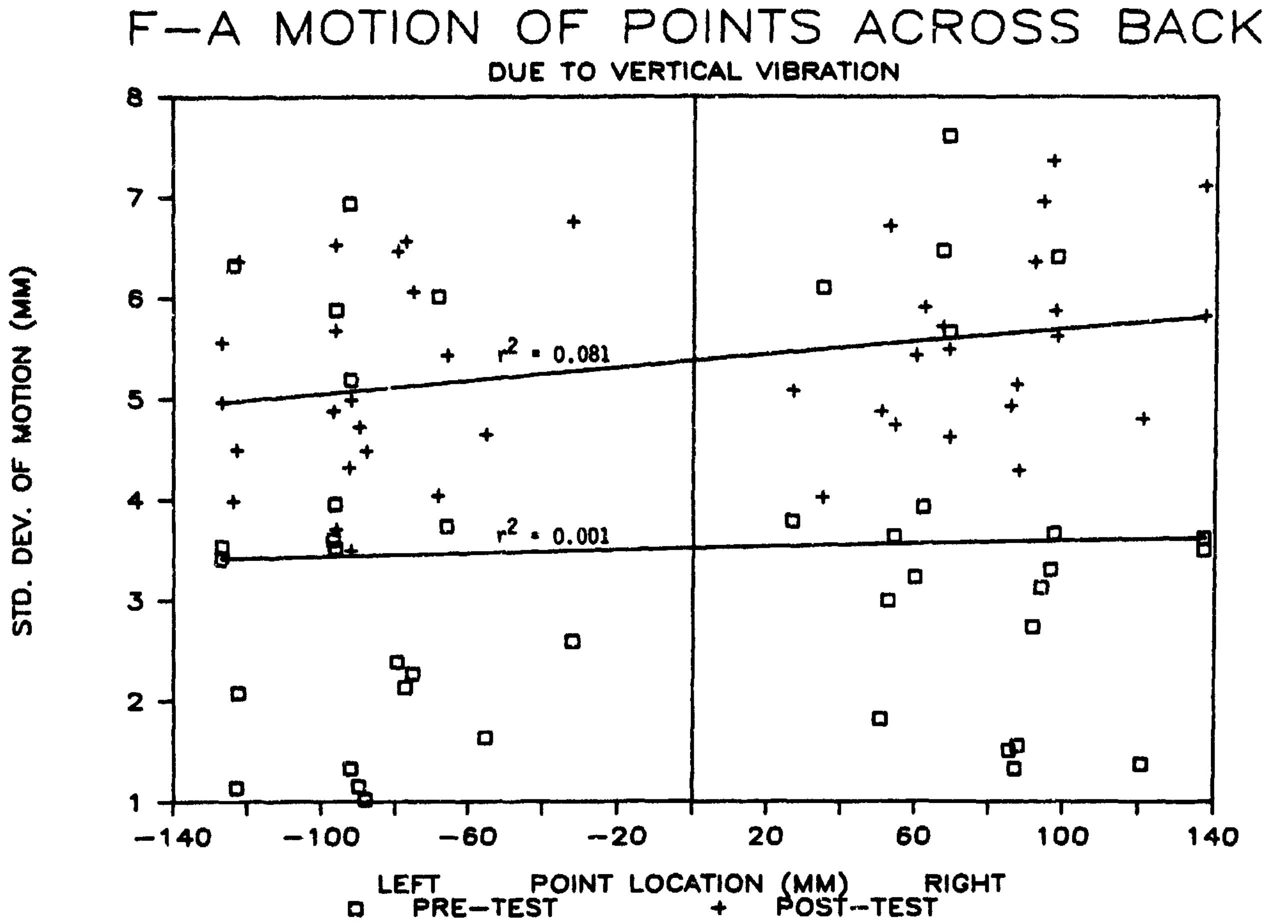


Figure 88. Linear regression of standard deviation of the fore-aft positions of each of the points across the top of the back with their location across the back due to a two-hour exposure to UH-1H specific up-down vibration. Data are from four subjects.

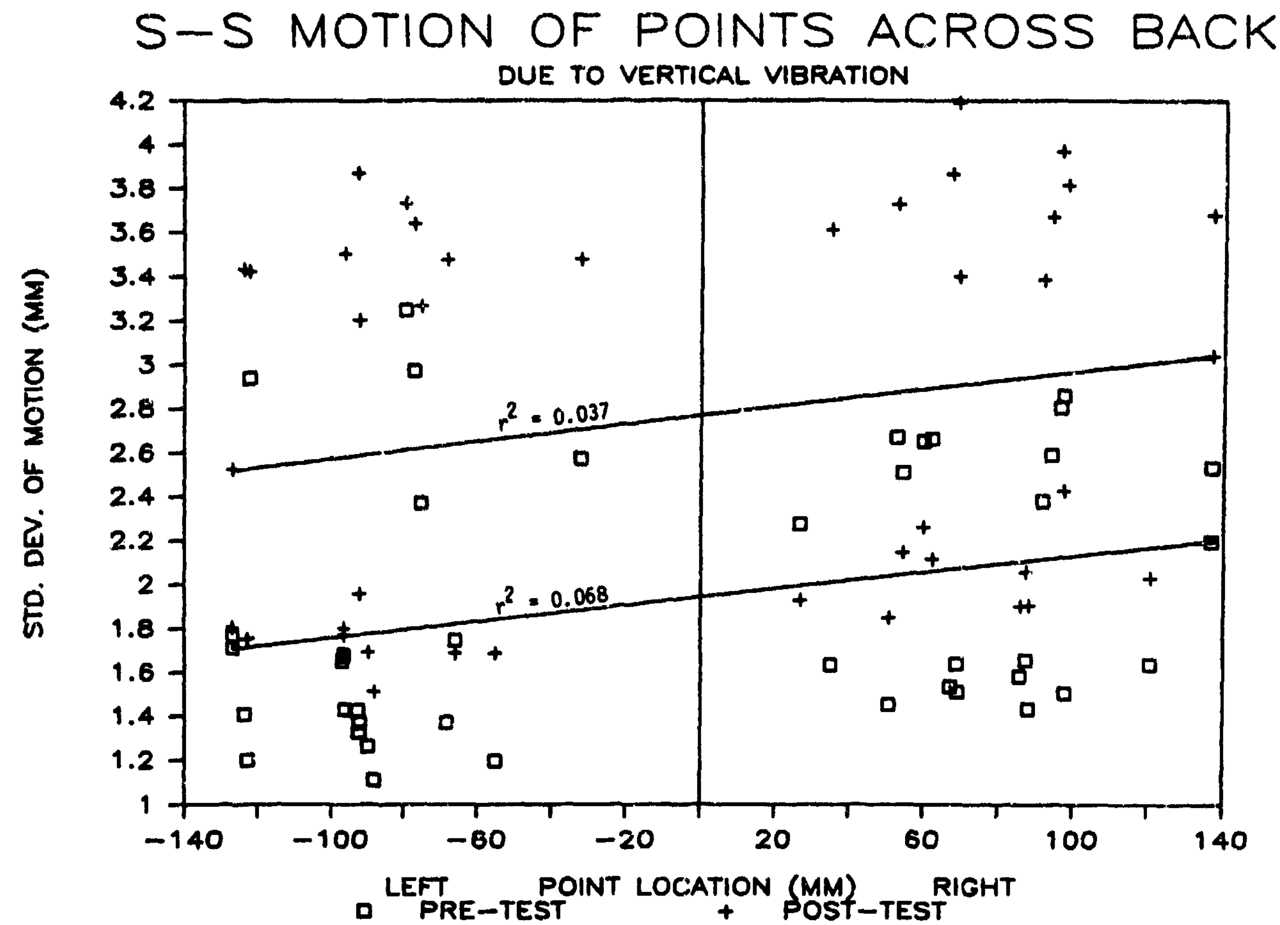


Figure 89. Linear regression of standard deviation of the side-side positions of each of the points across the top of the back with their location across the back due to a two-hour exposure to UH-1H specific up-down vibration. Data are from four subjects.

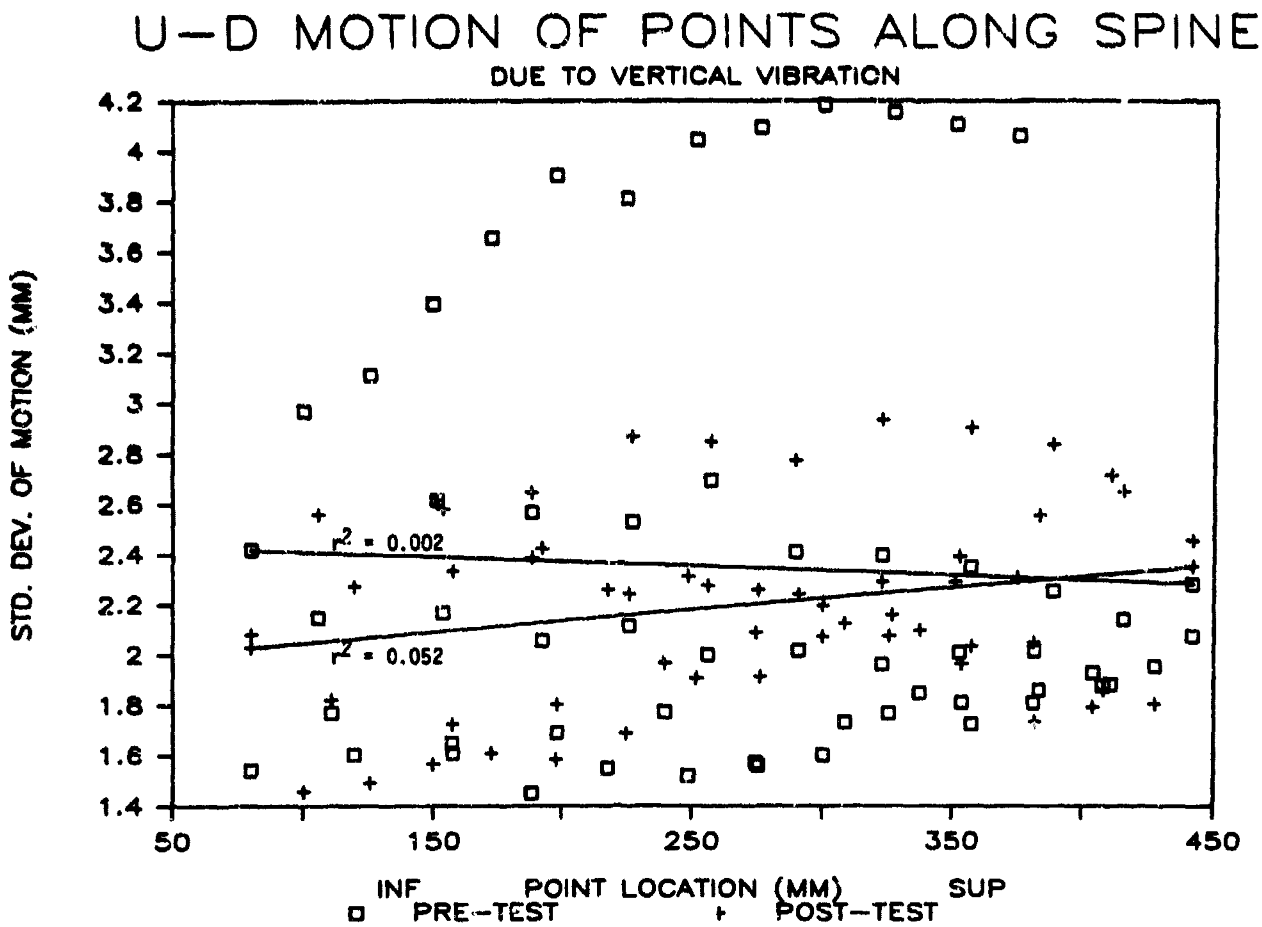


Figure 90. Linear regression of standard deviation of the up-down positions of each of the points along the spine with their location along the spine due to a two-hour exposure to UH-1H specific up-down vibration. Data are from five subjects.

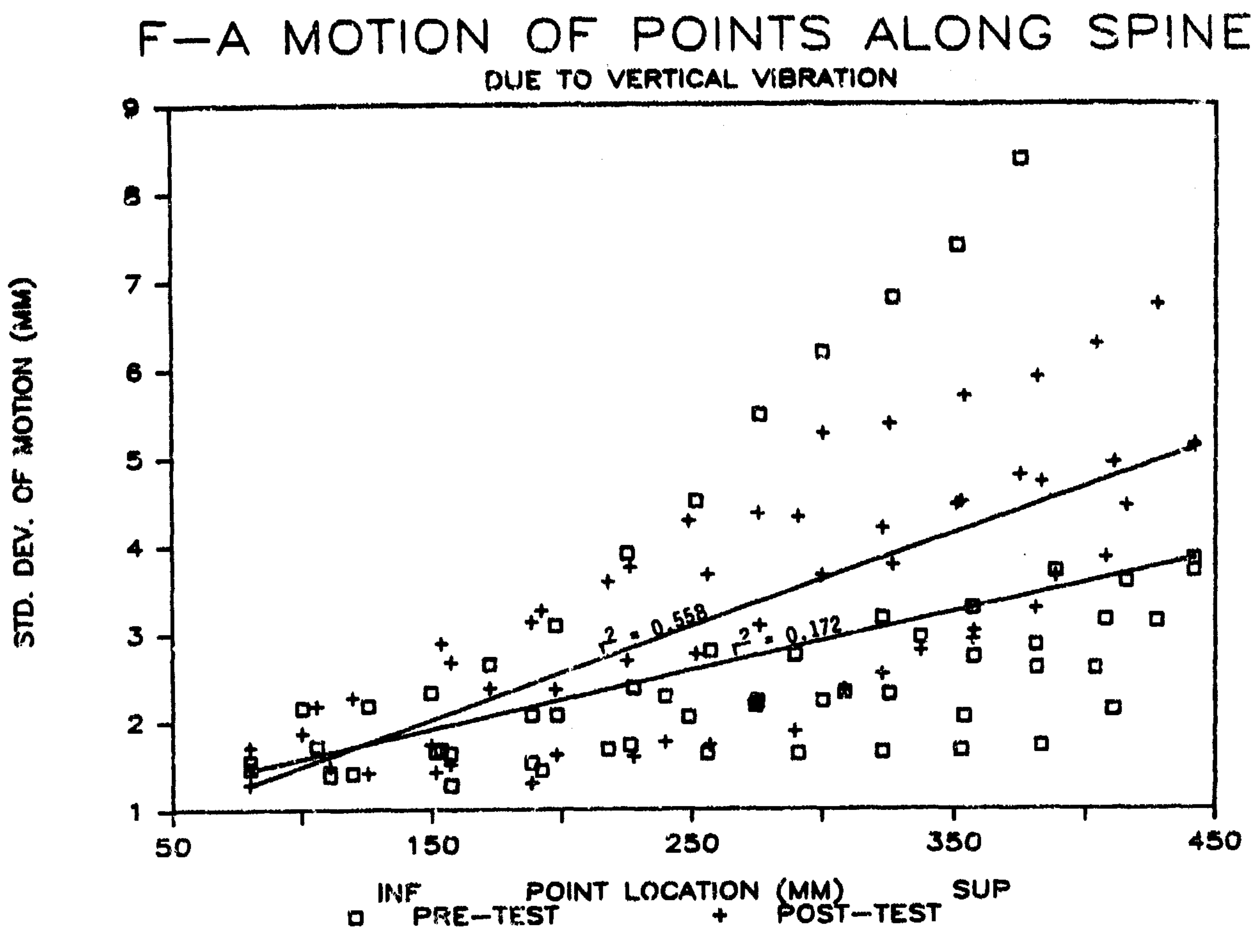


Figure 91. Linear regression of standard deviation of the fore-aft positions of each of the points along the spine with their location along the spine due to a two-hour exposure to UH-1H specific up-down vibration. Data are from five subjects.

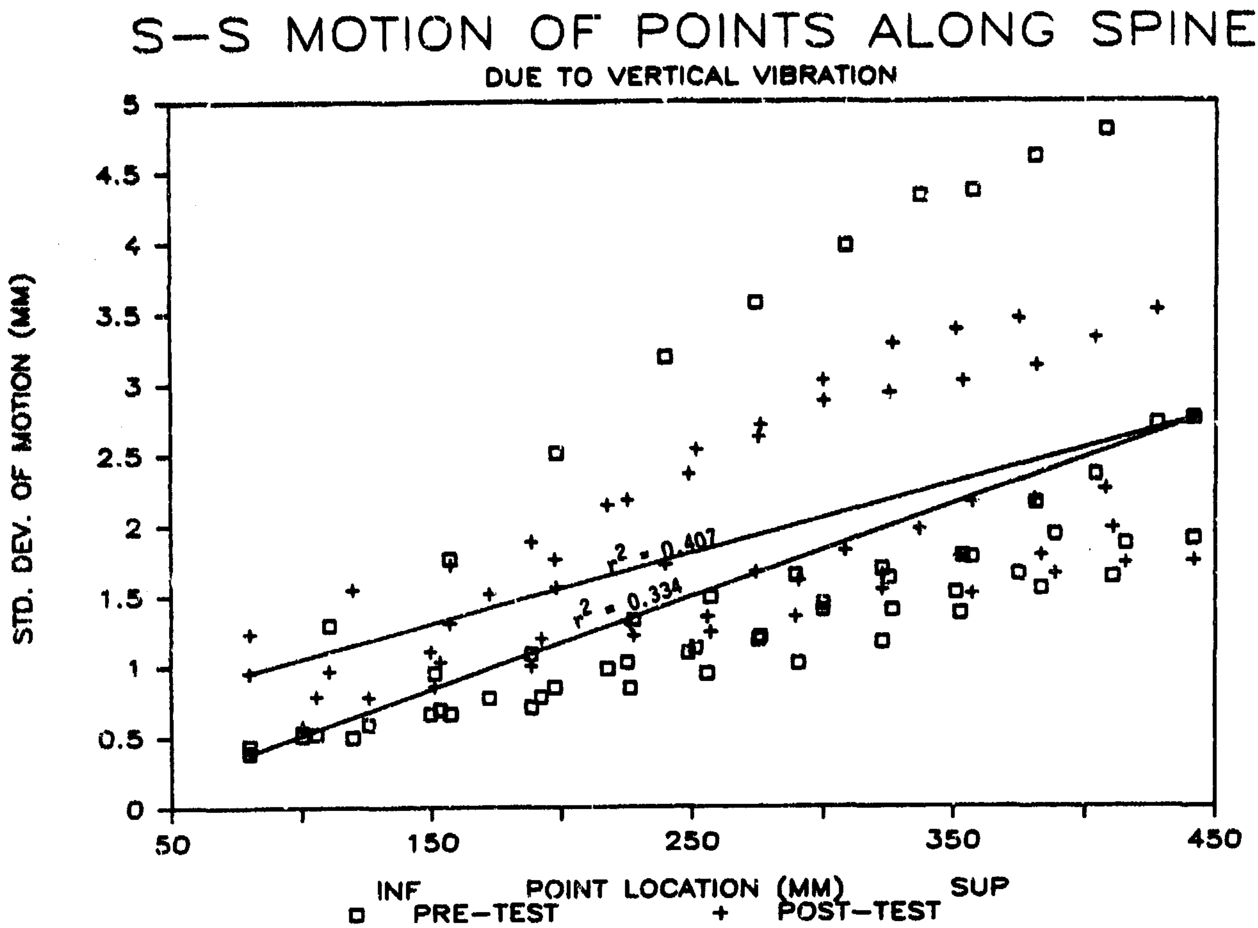


Figure 92. Linear regression of standard deviation of the side-side positions of each of the points along the spine with their location along the spine due to a two-hour exposure to UH-1H specific up-down vibration. Data are from five subjects.

side-to-side motions (Figures 88 and 89) indicate an increase in motion due to the exposure (both significant at the $p < .005$ level). There was essentially no change in the up-and-down motion of the points (Figure 87) across the back.

Motion of the points along the spine exhibit monotonically increasing values in both the side-to-side (Figure 92) and fore-aft (Figure 91) vibration modes. However, the up-and-down (Figure 90) motion, on average, appears constant along the spine. In terms of the changes in motion occurring due to exposure to seated vibration in the points along the spine, the changes are greater at the base of the spine than at the upper spine for the up-and-down and side-to-side motion. The opposite occurred with the fore-aft motion: there was a greater change in response of the upper spine than at its base and the overall change was not very significant ($p < .05$). This response may reflect the body's need to keep the head from shaking in a plane normal to the line of vision, whereas it may not be as sensitive to head motions along the line of vision.

Results conflict, however, when comparing the average side-to-side motion of points across the back to the side-to-side motion of the uppermost points along the spine.

CONCLUSIONS

Helicopter seat and cockpit design would benefit from a more ergonomically oriented design which provides good support for the pilot's back and an increase in the back-femur angle. This is so because the posture maintained is the factor more significantly associated with fatigue and pain in the UH-1H seating/cockpit environment.

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